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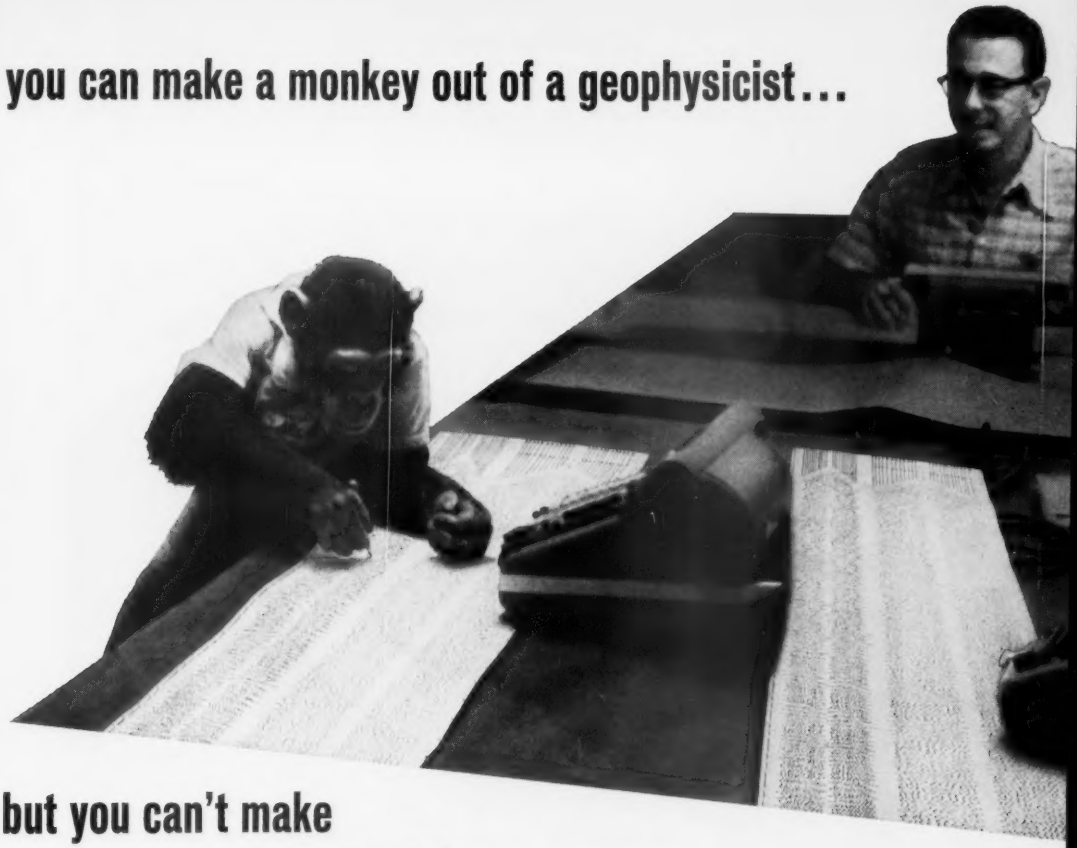

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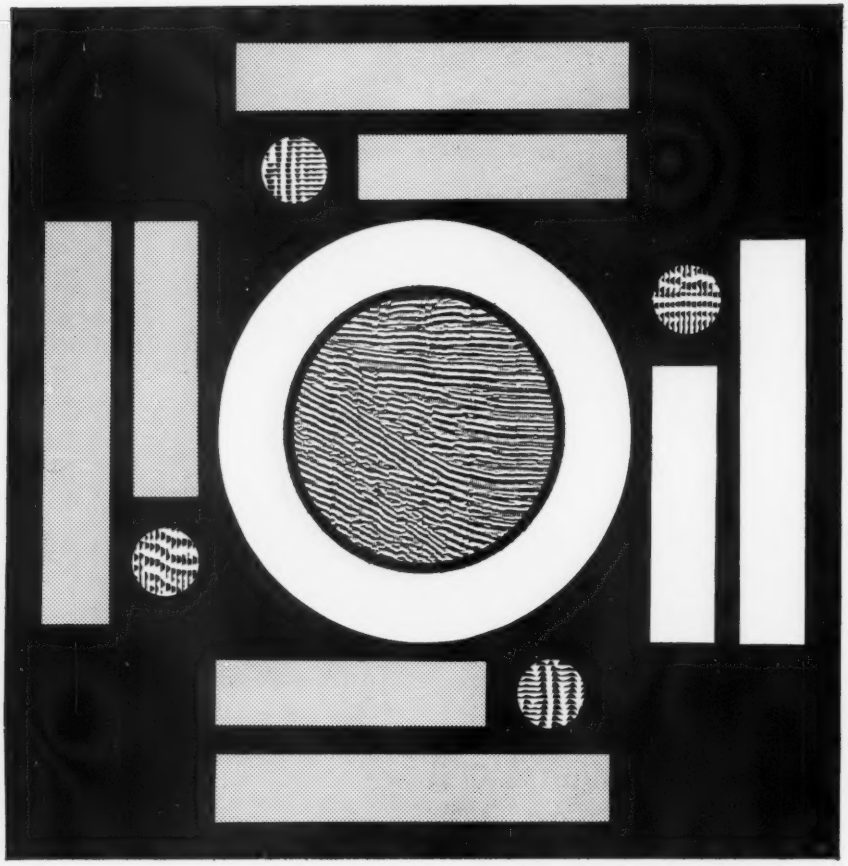

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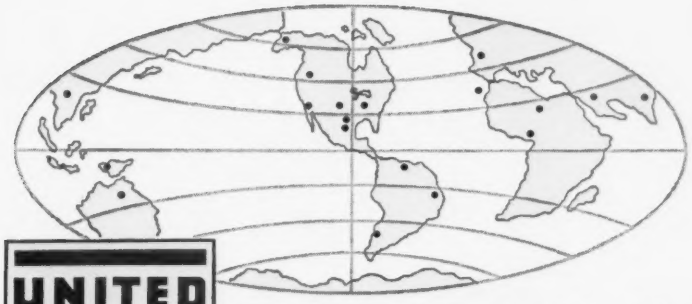

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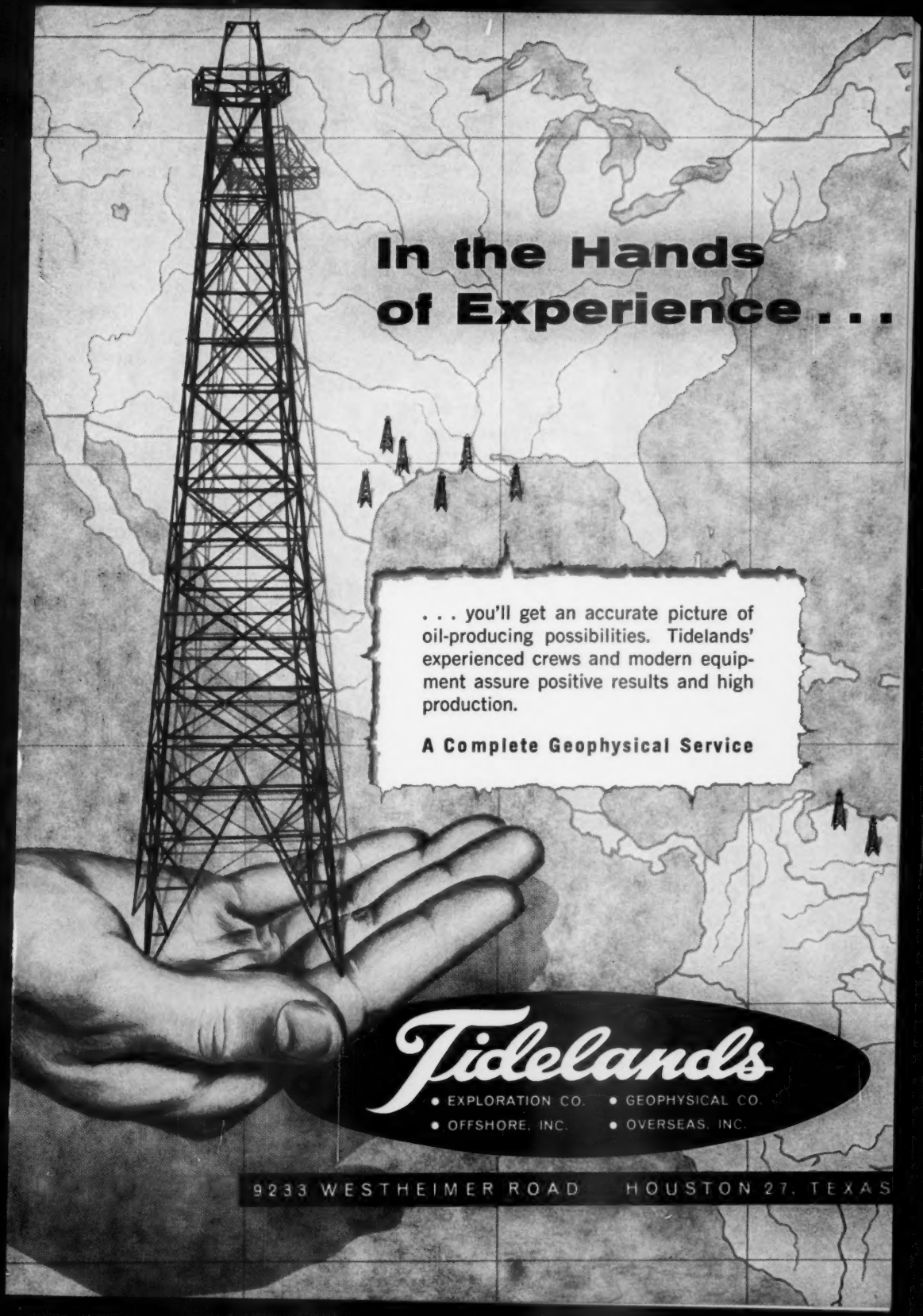
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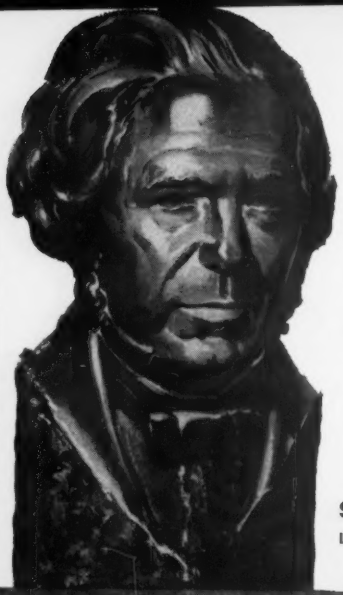

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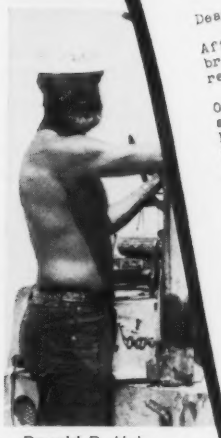

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Volume XXVI DECEMBER, 1961 Number 6

GEOPHYSICS

CASE HISTORY—DESERT SPRINGS GAS FIELD SWEETWATER COUNTY, WYOMING*

JOHN H. EARL† AND JOHN N. DAHM†

Desert Springs Area is located in central Sweetwater County, Wyoming, on the west flank of the Red Desert Basin, with the Rock Springs uplift to the west and the Wamsutter arch to the south.

The producing reservoirs are in the Upper Cretaceous Lewis and Almond formations, with the Almond being the uppermost formation of the Mesaverde Group in the area.

Petty Geophysical Engineering Company was contracted to conduct a seismic survey over the area. Work was initiated on April 3, 1956 and completed July 24, 1956.

Fault evidence was noted in the area, based on discontinuity of seismic events and change of reflection characteristics. On the basis of this fault evidence, El Paso Natural Gas Company drilled the Desert Springs No. 1 well which potentialed for 7.7 million cubic feet of gas per day. This led to additional drilling; and, as of January 1959, eight wells have found production at an average depth of 6,100 ft, having potentials from 7.7 million cubic ft of gas per day with some distillate.

A detailed study of stratigraphy, lithology, and sedimentation, along with a detailed review of the seismic data utilizing the velocity survey in Desert Springs No. 1 well, was undertaken. The final analysis revealed that the phenomena originally mapped as a fault is in reality a series of facies changes. Three main stratigraphic type traps: offshore bar, lateral facies change, and wedge-out below an unconformity; are believed to be present in this area, thus making an integrated and coordinated exploration program between the geologists and the geophysicist necessary if we expect to find additional oil and gas reservoirs of this nature.

INTRODUCTION

The Desert Springs area is located in T20-21 N, R97–98W in central Sweetwater County, Wyoming, on the west flank of the Red Desert Basin (Figure 1).

The Rock Springs Uplift is to the west and the Wamsutter Arch is located to the south. The reservoirs are in the Upper Cretaceous Lewis and Almond Formations, the Almond being the uppermost formation of the Mesaverde Group in the area. Other Upper Mesaverde gas accumulations in the area are the recent Mud Lake, Wamsutter, Forest Oil Company, Texas National discoveries; the older Table Rock and Southwest Table Rock Fields. Table Rock and Southwest Table Rock fields are gas productive also from the Lewis.

GEOPHYSICAL HISTORY

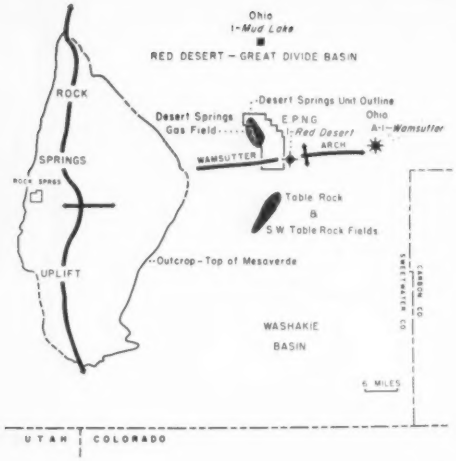
The seismic work in the Desert Springs Area was initiated for two reasons, the proximity of this area to the Table Rock Field to the south and the similarity of the Almond Section in the El Paso Natural Gas Red Desert No. 1 dry hole to that in the Table Rock Field.

Petty Geophysical Engineering Company's Party 10 was contracted to do the survey. Work was initiated on April 3, 1956 and completed July 24, 1956.

Continuous subsurface profiling was obtained by using the conventional split spread with 24 traces being recorded with Petty Geophysical Company Model H Amplifiers and 4 Technical Instrument Company land seismometers per group at 20-ft intervals. A 1,320-ft interval be-

* Manuscript received by the Editor March 22, 1961.

† El Paso Natural Gas Company, El Paso, Texas.

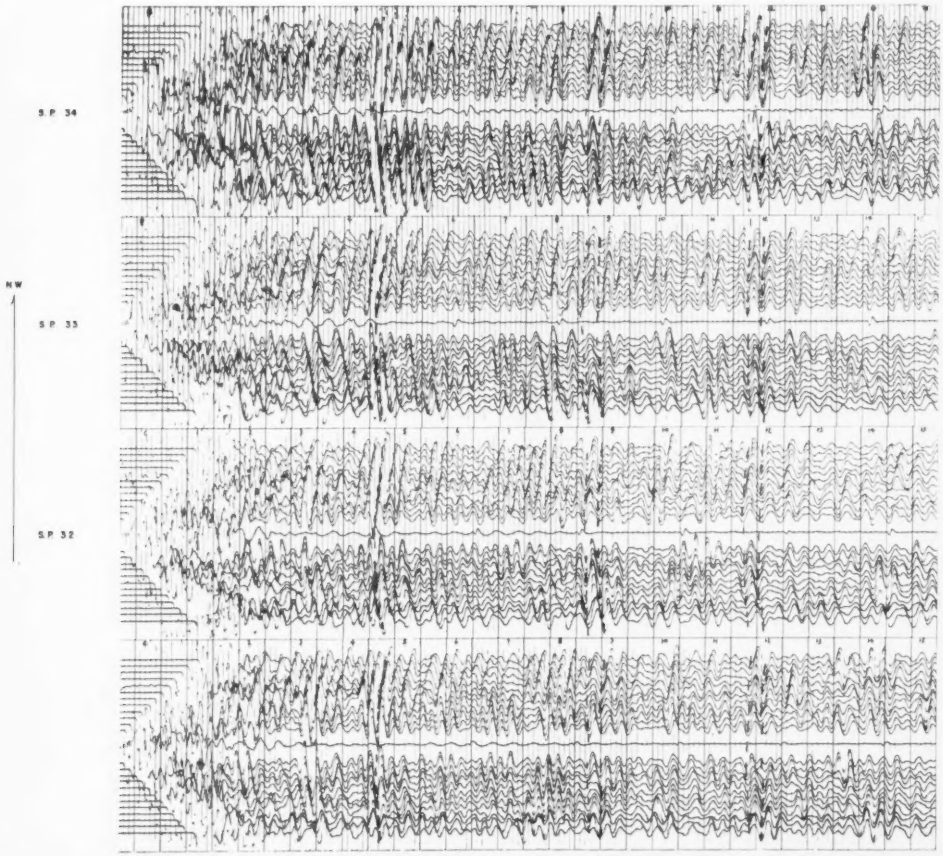


tween shotpoints, with the center of the first group 160 ft from the shotpoint and succeeding groups centered 100 ft apart, left 40 ft between the last detector in one group to the first detector in the following group.

A small amount of electrical mixing between channels amounting to one trace overlap was used for all traces except 12 and 13. No. 11 is 75 percent 11 and 25 percent 12. No. 10 is 75 percent 10 and 25 percent 11, and so on to trace one which is 75 percent 1 and 25 percent 2. Likewise

FIG. 1. Index map showing Desert Springs and adjacent gas fields, Sweetwater County, Wyoming.

FIG. 2. Specimen records, Desert Springs area.



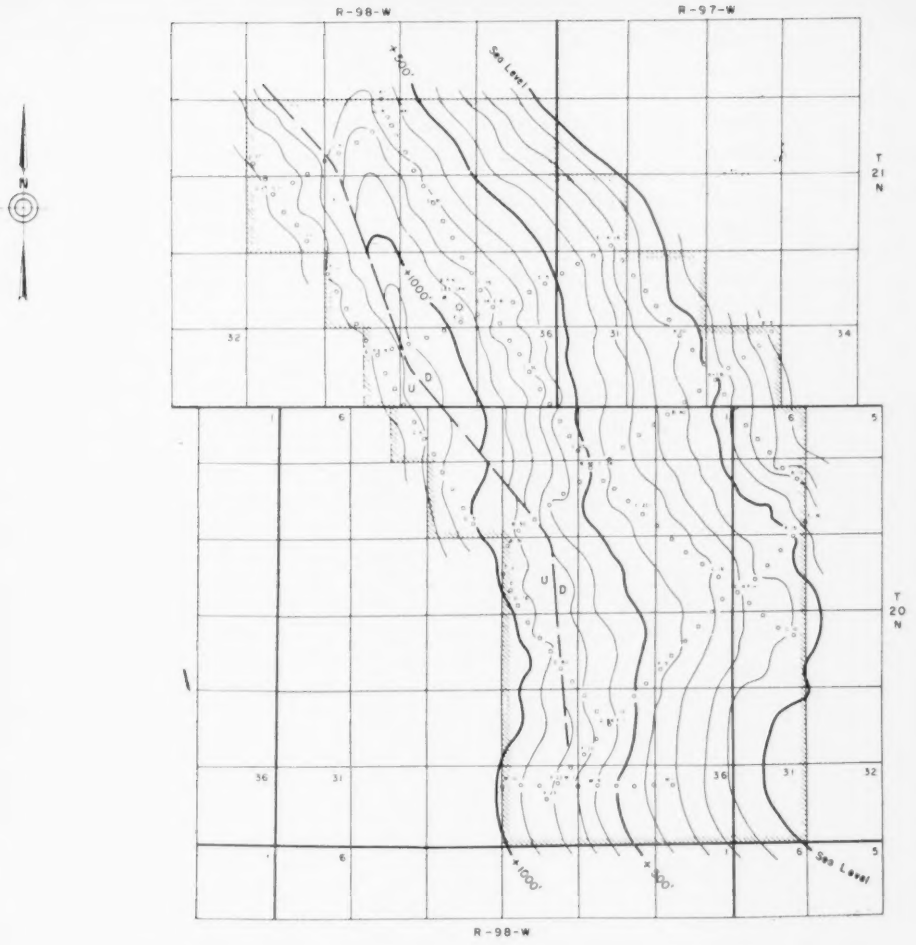


FIG. 3. Desert Springs area Sweetwater County, Wyoming. Mesaverde Horizon.

on the other side of the shotpoint, No. 14 is 75 percent 14 and 25 percent 13.

Filter settings were in the range of 20–50 to 40–70, 20 to 40 cycles on the low cut and 50 to 70 cycles on the high cut. The higher frequency broader band settings generally gave the better results.

Dual recording was employed, enabling two records to be taken simultaneously; one mixed as previously mentioned and one straight or no electrical mix. Record quality was generally fair to good as shown in Figure 2 where Ft. Union-Lewis-Mesaverde reflections are noted.

Velocity used in the construction of the time depth conversion chart was based on the survey in the Texas Company No. 5 Table Rock Well located in Section 2, T 18N-R 98W.

Three maps were prepared on this project, No. 1 Fort Union-Tertiary, No. 2 Lewis Horizon-Upper Cretaceous and No. 3 Mesaverde-Upper Cretaceous.

The Mesaverde horizon, being the prime objective, will be discussed first.

Figure 3 presents the interpretation submitted

at the conclusion of the survey on a reflector in the Mesaverde. The fault trace is based on the discontinuity of seismic events and the abrupt change of reflection characteristics as shown in Figure 4. Closure of several sections extent is shown on the downthrown side of the fault.

Accordingly, El Paso Natural Gas Desert Springs No. 1, was located in the CS E/4, Section 26, T 21N-R 98W and completed in the Mesaverde for an indicated open flow potential of 7.7 million cubic feet of gas per day. This location is shown in Figure 5.

This discovery well led to additional drilling. As of January, 1959, El Paso Natural Gas had drilled five gas wells. Gulf has one well, and Pubco has two wells. Average depth of these wells is 6,100 ft. All are presently shut-in awaiting an outlet.

As well control in the area became available, the presence of the fault became increasingly uncertain. A detailed review of the seismic information, employing a trace by trace analysis, was undertaken utilizing the velocity survey in the El Paso Natural Gas Desert Springs No. 1. In conjunction with this review, a study of the stratigraphy, lithology, and sedimentation was made by El Paso's laboratory in Salt Lake City. The geologic explanation of what was first interpreted as a fault will be evident from the following discussions of the stratigraphy.

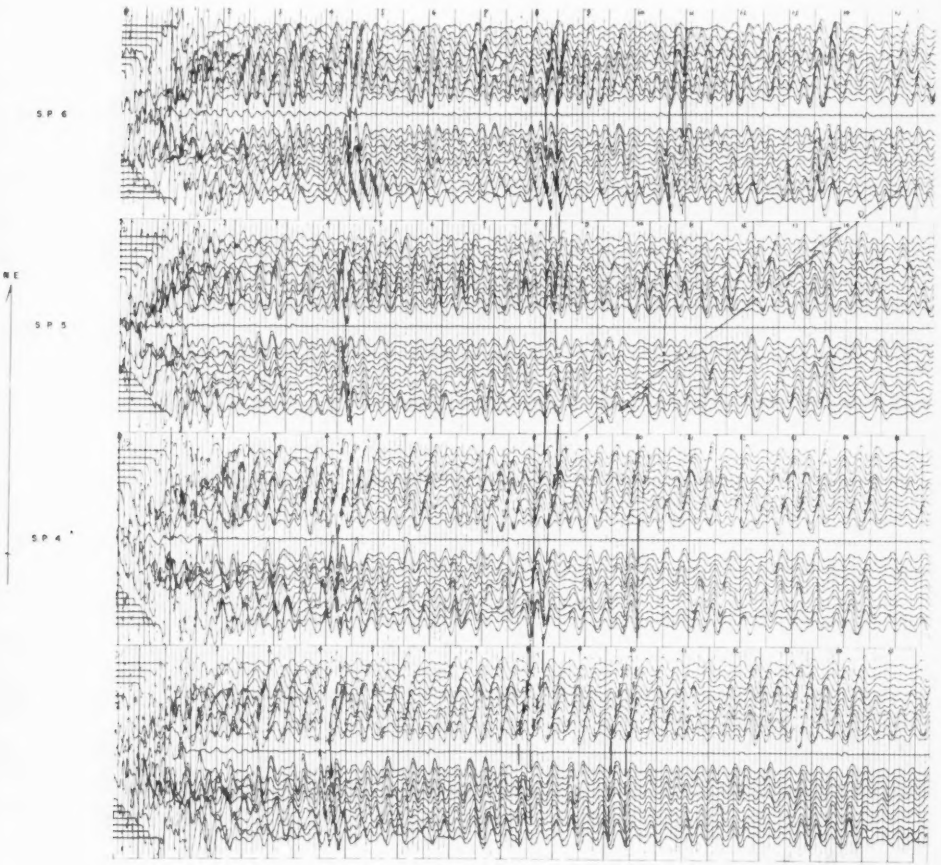


FIG. 4. Records across possible fault area.

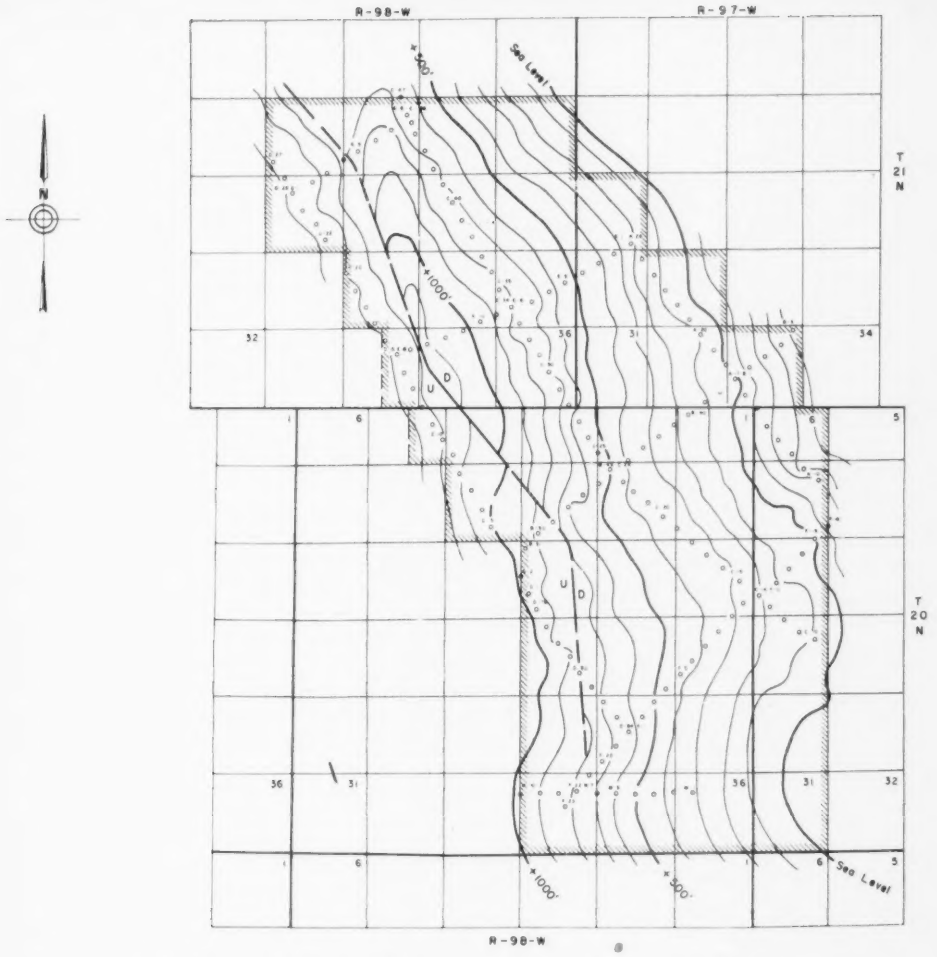


FIG. 5. Desert Springs area Sweetwater County, Wyoming. Mesaverde Horizon.

STRATIGRAPHY, LITHOLOGY, AND SEDIMENTATION

Figure 6 is a west to east restricted stratigraphic cross-section through the field. The line of section is shown on the location map, and includes the following wells, from west to east: Pubco No. 34-1, El Paso No. 4 Unit, Gulf No. 1 State-May, then southward to El Paso's No. 3 Unit. The portion of the stratigraphic section shown is from the basal Lance Formation of the Uppermost Cretaceous, through the Lewis shale, terminating in the Almond and Ericson formations of the Mesaverde. To date, the Ericson is the oldest formation which has been drilled within the field.

LEWIS *E*-SAND

The descending zonation, *A* through *H*, of the Lewis shale is based largely on characteristic deflections of the resistivity curves on the electrical logs.

The lenticularity of the Lewis *E*-sand is indicated on the cross-section, and this local build-up of sand is interpreted as being an off-shore bar

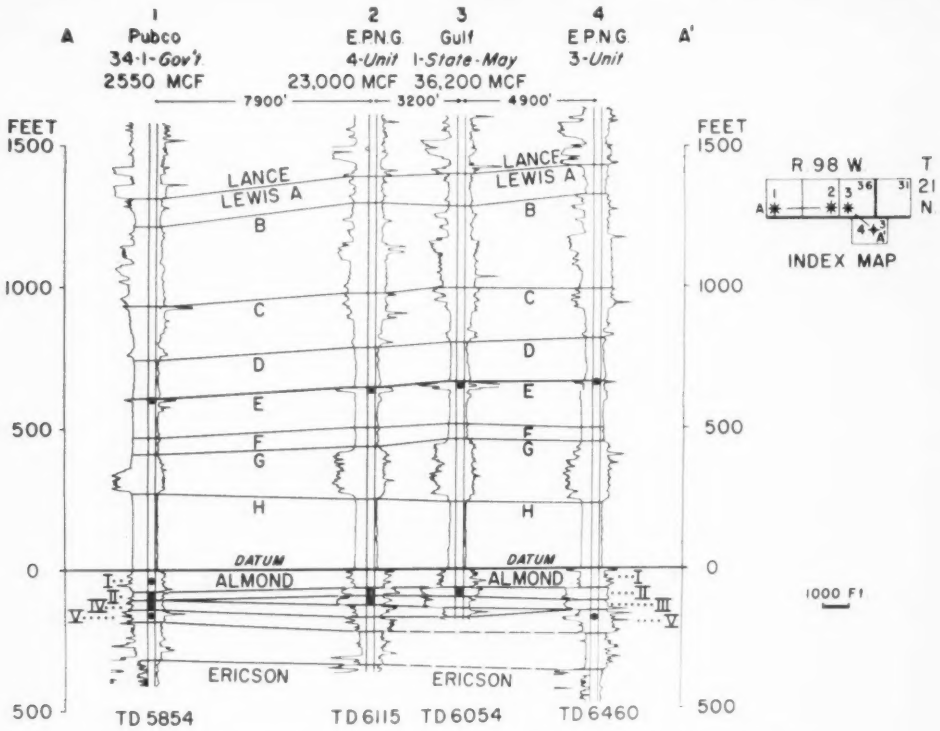


FIG. 6. Desert Springs field stratigraphic cross-section *A-A'* datum top of almond formation.

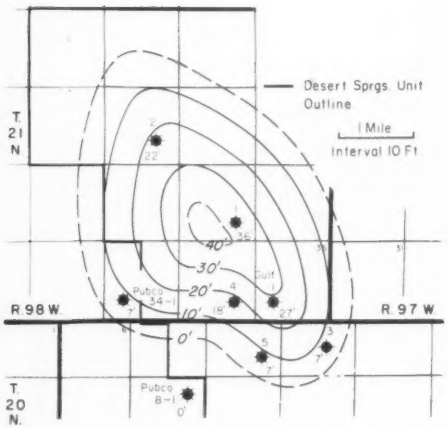


FIG. 7. Desert Springs field Isopachs Lewis *E*-sand.

of submarine sandbank. Limited micro-paleontologic data indicate an upper neritic environment. The bar seems to represent a short period of stability of the Lewis shoreline. Based on limited coring, the sandstone is described as a graywacke, following Pettijohn's classification. The grain size is from siltstone to medium, and the average is in the very fine to fine range. The grains are angular to sub-angular, and the sorting is poor to fair. The sand is poorly cemented, calcareous, and micaceous.

Figure 7 is an isopach map of the gross thickness of the Lewis *E*-sand. The thicknesses are derived from the electrical logs and range from zero feet in the Pubco 8-1 well to 36 ft in the El Paso Natural Gas No. 1 Unit. The El Paso Natural Gas No. 6 Unit was drilled after Figure 7 was made. This well, which is located approximately one mile south of the El Paso No. 5 Unit, has 7 ft of gross sand; thus, the bar is either ex-

tended southward or another one has been located.

Well potentials in the Lewis *E*-sand, after fracturing treatments, range from 2.5 million cubic feet per day in the Pubco No. 34-1 well to 23 million cubic feet per day absolute open flow in the El Paso No. 4 Unit. The reservoir carries distillate, and no producible water is evident. As Figure 7 indicates, the lateral limits of this reservoir have not been well defined.

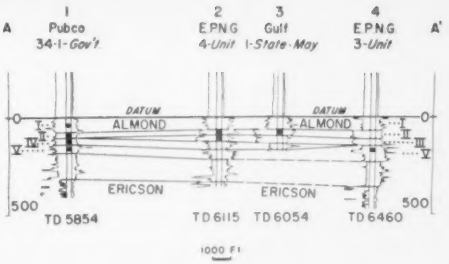


FIG. 8. Desert Springs field details of almond formation in cross-section *A-A'*.

ALMOND FORMATION

Figure 8 shows the lower part of Figure 6 enlarged. The Almond formation has been zoned in descending order into five zones. The zonation is based on distinctive deflections of the resistivity curves on the electrical logs. These characteristic resistivity patterns are caused by the thin coal beds and the black carbonaceous shales between the sands. Detailed core examination indicates that the sands in Zones I and V fall in Pettijohn's sub-graywacke category. The sand grains are

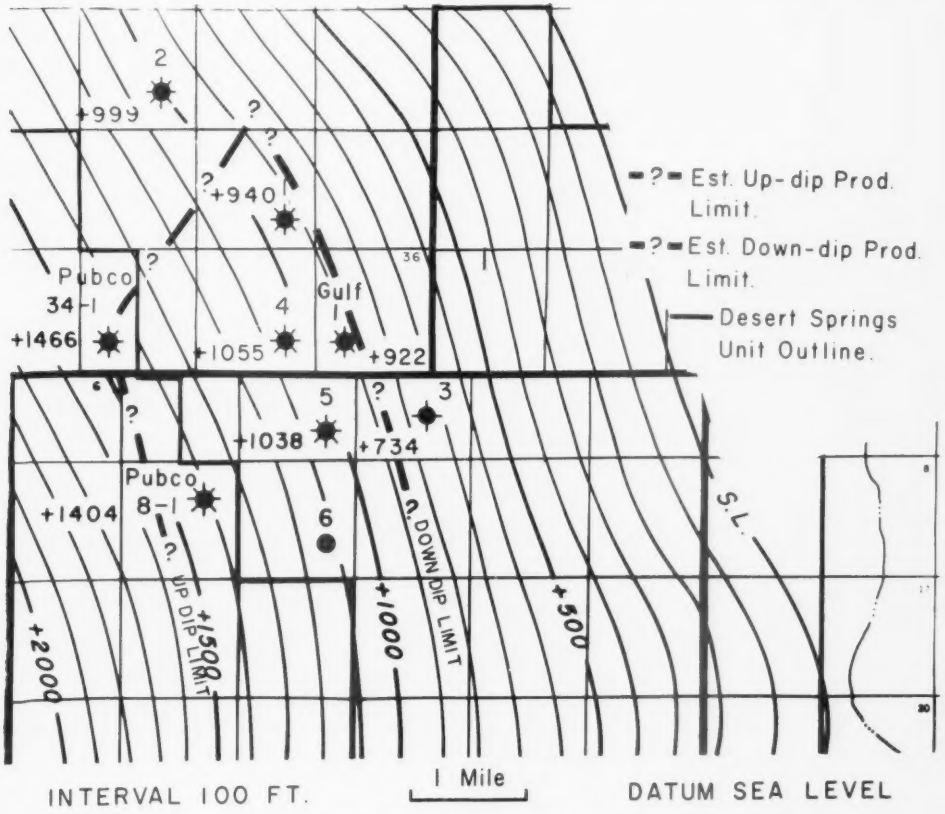


FIG. 9. Desert Springs field structure—top of almond.

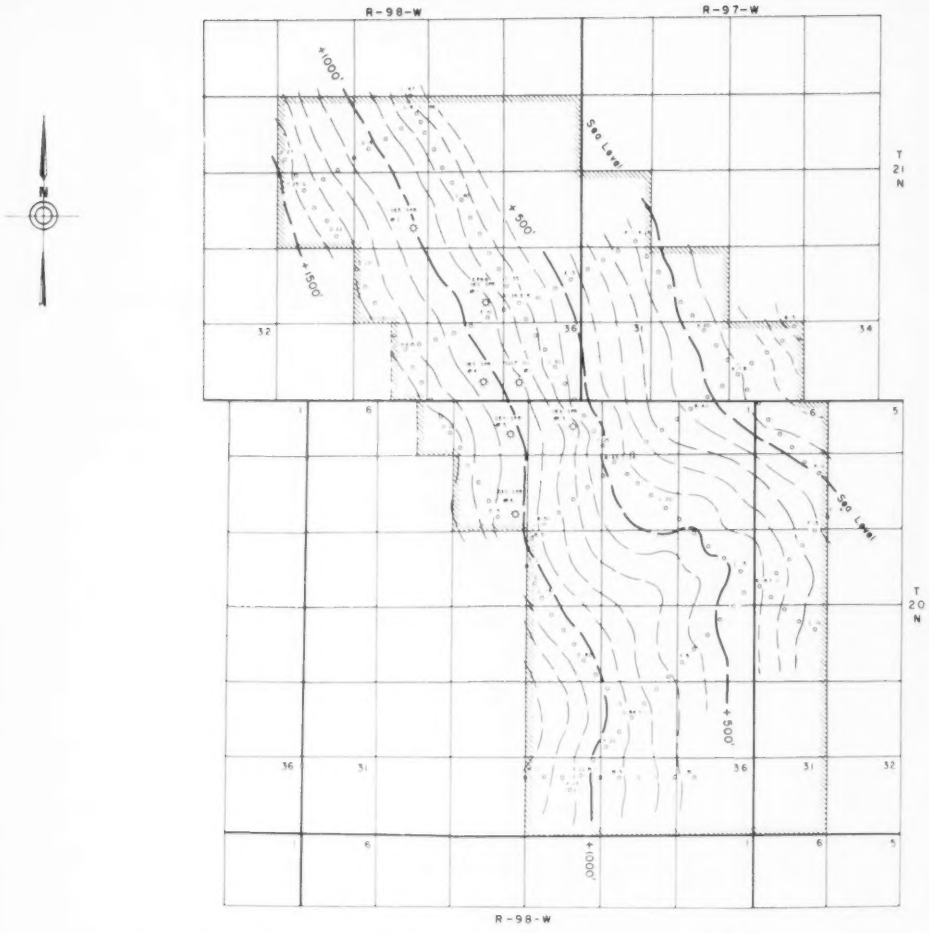


FIG. 10. Desert Springs area Sweetwater County, Wyoming. Mesaverde Horizon.

well sorted, and the average grain size is in the coarse to fine sand range. Thin coal beds sometimes cap the sands. Occasional oyster beds are foundi n the sands and the shales.

The following discussion will be limited to Zones II through V because of the scarcity of data on Zone I.

Cores and electrical logs indicate that the trap in Zone II is due to an up-dip lateral facies change. The change is from very fine sand into siltstone and shale. The net effect is a permeability barrier. This trap is between the Pubco No. 34-1 and the El Paso No. 4 Unit wells.

It is believed that the trap in Zone III has a dual origin. It is possibly an up-dip wedge-out of the sand due to a diastem in combination with a lateral facies change into finer clastics. An alternative hypothesis is that no unconformity is present, and there is only a lateral facies change as in Zone II. If there is a lateral facies change, zone labeled No. II in the Pubco No. 34-1 well would then be Zones II and III undifferentiated.

Zone IV, as yet unproductive, is interesting because it seems to wedge-out southward due to a diastem. The cross-section shows that it wedges out between the Gulf No. 1 State-May and the El Paso No. 3 Unit.

In addition to being absent between the Gulf

well and the El Paso No. 3 Unit, Zone IV is absent in the El Paso No. 5 and No. 6 Unit wells and the Pubco No. 8-1 well. Thus a southward wedge-out is indicated.

The basal part of Zone V recently was proven productive in El Paso Unit No. 6, located approximately one and one-half miles southwest of the El Paso No. 3 Unit. It is a new sand development which seems to be a lateral facies change from the finer clastics at the base of Zone V in the El Paso No. 3 Unit. The upper portion of Zone V in the El Paso No. 3 Unit is a possible recompletion zone, based on calculations from the electrical-induction log.

The depositional environment of the Almond is interpreted as follows:

The carbonaceous black shales with occasional coal and oyster beds are believed to have been deposited in a coastal swamp, and the source area is thought to have been to the west. The sands in Zones II and III are believed to have been deposited in a near-shore marine environment.

As of January, 1959, four wells have been completed in the Almond (Figure 9). The El Paso No. 4 Unit is capable of good production, and the Pubco No. 34-1 is a "near producer."

Well potentials in the Almond, after fracturing treatments, range from 7.7 million cubic feet per day in the El Paso No. 1 Unit to 41 million cubic feet per day absolute open flow in the El Paso No. 6 Unit. All of the reservoirs carry distillate.

The broken lines show the estimated up-dip productive limit and estimated down-dip productive limit of the Almond. The down-dip line actually is the gas-water interface at the bottom of Zone II, as established by drill-stem testing in the Gulf No. 1 State-May. Data on the gas-water interface in Zone III indicate that it is structurally higher than the interface in Zone II.

The Almond reservoirs have not been very well delineated; and future expansion of them is to be expected, particularly southward.

The structural picture based on the review and integration of all possible geological and geophysical data is shown on Figure 10. It appears that the break in seismic correlation which was interpreted as a fault was more likely a change in character induced by marked lateral variations in stratigraphy. Consequently, in a certain sense the discovery of Desert Springs Field was fortuitous circumstance based upon an incorrect interpretation of seismic data. However, in another and very real sense it can be considered a geophysical success since there is present a definite seismic anomaly. The limited resolution of the seismic method precludes the possibility, at least at this time, of correctly interpreting such seismic anomalies without benefit of well data. However, this discovery demonstrates that the seismic method can, in some cases, contribute to the search for stratigraphic accumulations in spite of our inability to interpret fully what is seen on the records.

GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 682-690, 9 FIGS.

GEOPHYSICAL CASE HISTORY OF THEUVENINS CREEK FIELD, TYLER COUNTY, TEXAS*

T. Y. CHANG†

Theuvenins Creek Field is located along the Wilcox producing trend in south-central Tyler County, Texas. The field was discovered jointly by Sinclair Oil and Gas Company and the Atlantic Refining Company.

The first seismic survey of the area was made in 1938. In 1942, a reconnaissance seismic survey was made using the spot correlation method. This work indicated anomalous conditions. In 1955, the area was detailed using a continuous seismic profile method. The seismic data were later reviewed, and the reviewed interpretation substantiated the existence of Wilcox structural closure.

Based on seismic evidence, Atlantic and Sinclair spudded the Brown Fee No. 1 wildcat well on August 15, 1957. This well was completed on October 12, 1957 as the discovery well of the field. From an Upper Wilcox sand the well produced 279 barrels of oil per day. Subsequent drilling developed two producing sands in the Uppper Wilcox. A total of 38 producing wells have been drilled on the structure with no dry hole to date. To January, 1961, the total cumulative production from the field was 1.4 million barrels of oil.

INTRODUCTION

Theuvenins Creek Field was discovered in 1957. The field produces oil from the Wilcox at a subsea depth of 8,300 ft. The discovery well, drilled on a seismic "high," was a joint exploratory test by Sinclair Oil and Gas Company and the Atlantic Refining Company. Seismic exploration was conducted intermittently in the area during the period from 1938 to 1956.

REGIONAL SETTING

Theuvenins Creek Field lies in south-central Tyler County, Texas, about 15 miles northwest of Silsbee Townsite (Figure 1). The surface consists of low, rolling hills lying along the transition zone between the flat, coastal plain to the south and deeply dissected hills to the north. The terrain is covered with a dense stand of pine and hardwood timber.

The field lies along the Wilcox producing trend of the Gulf Coast Region. Joe's Lake Field, located 9 miles to the northeast, and Segno Field, 15 miles to the southwest, have produced from the Wilcox formation for many years. About 20 miles to the south, Batson, Saratoga, and Arriola fields lie on the northern rim of the Gulf Coast Salt Dome Basin. These fields produce from the Miocene, Frio, and Yegua.

SEISMIC EVALUATION

The first seismic survey in the Theuvenins Creek area was made in 1938 by McCollum Exploration Company. The survey was reconnaissance in nature and control was sparse. McCollum used the "spot correlation" method of shooting with a 750 ft spread laid across the shot hole. Twelve traces per spread were used with one geophone per trace. Shotpoints were spaced about 4,500 ft apart along selected lines.

Figure 2 shows an interpretation of seismic data shot by McCollum based on correlation of a reflection about 300 ft below the top of Wilcox. The map is contoured on a 100 ft interval. The small circles represent shot holes and clearly indicate the limited amount of control obtained. This map indicates some reverse dips in the vicinity with a closed high centering about $1\frac{1}{2}$ miles southwest of the discovery well. The axis of the high trends northeastward. No faulting was mapped. The present productive limits of the field are shown by the stipled area. The relationship between the early seismic interpretation and

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† The Atlantic Refining Company, Houston, Texas.

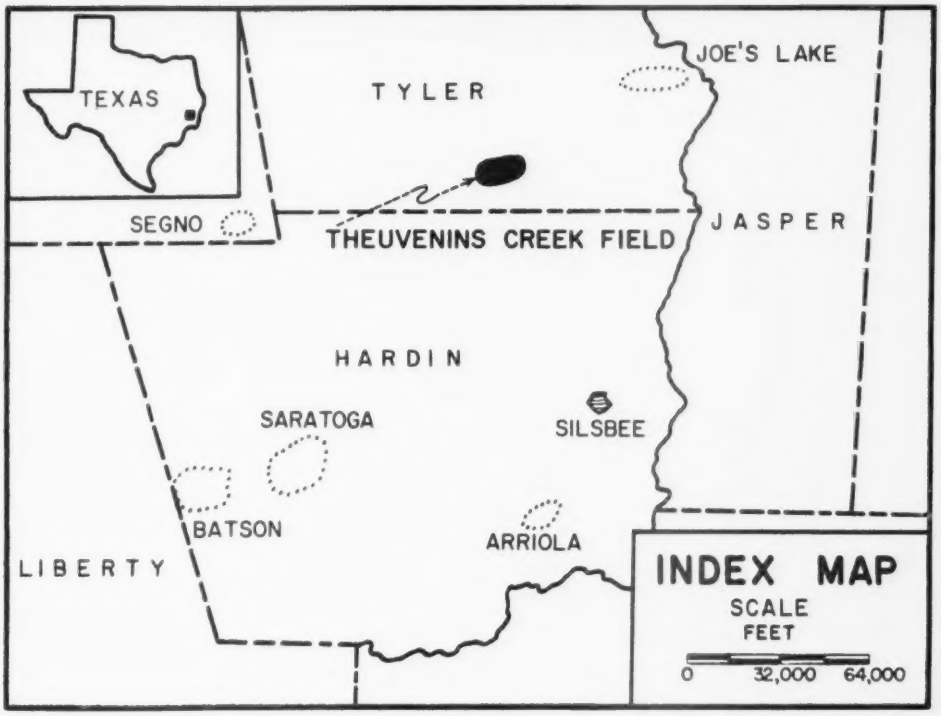


FIG. 1. Index map of portion of Southeast Texas showing location of Theuvenins Creek Field.

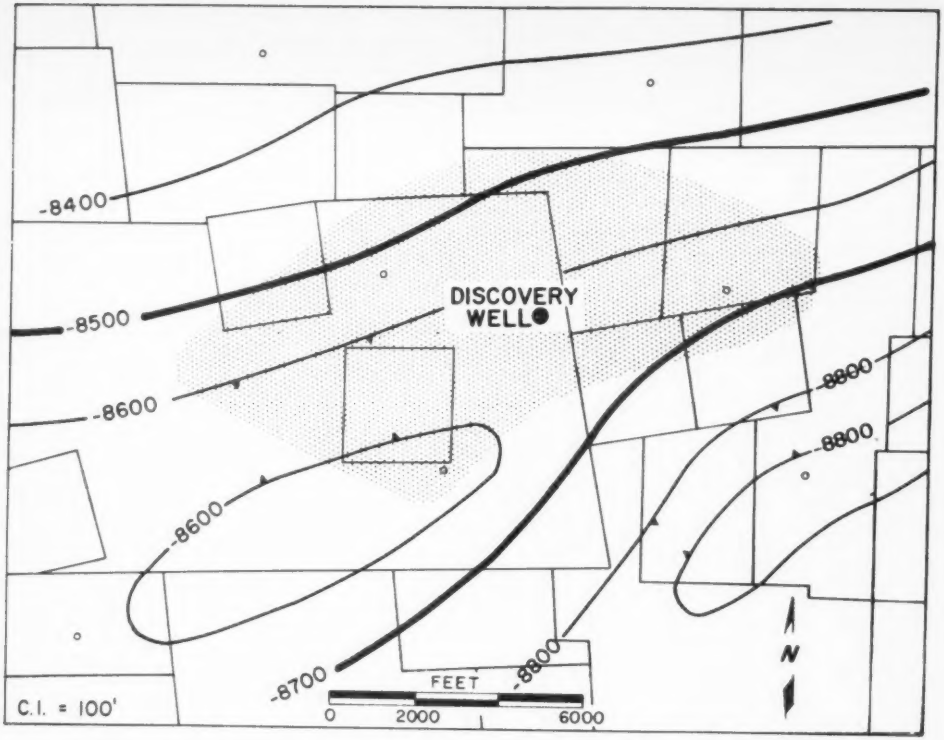
the productive area may be observed.

The anomalous conditions in the vicinity, indicated by the 1938 seismic work, were not considered very promising in the light of the standards of that time, and little interest was evidenced in Theuvenins Creek area by the companies controlling the fee land.

In 1942 additional seismic work was performed in the area by Seismic Explorations, Incorporated. SEI used the "spot correlation" method of shooting, and the survey was also principally of a reconnaissance nature. A 350-ft, six-trace spread was used, offset 2,600 ft from the shot hole. The shot hole and spread set-up was arranged so that a depth-point could be computed at 1,300-ft intervals along selected lines. Fair to good correlatable reflections were obtained by this method. The Wilcox reflection generally had outstanding characteristics.

Figure 3 shows an interpretation of the records obtained by SEI, based on a reflected event from a horizon approximately 200 ft below the top of Wilcox. The contour interval is 50 ft. An east-plunging, anticlinal type Wilcox structure was mapped, lying between two down-to-the-south major faults (*A* and *B*) trending in an east-west direction. The probability of a saddle was suggested near the western edge of the present productive area. Although the interpretation was based on very limited control, the essential features of this map have held up remarkably well under more detailed investigation later.

Following SEI's 1942 seismic work, the Theuvenins Creek area remained inactive for a period of 13 years. In December, 1955, a detailed seismic survey of the area was conducted by SEI. In this survey a 1,000 ft spread was used with the near trace offset 2,000 ft from the shot hole. The spread was laid in-line with the shot position, and holes were spaced 1,000 ft apart along selected lines. The long-offset shot and spread arrangement resulted in continuous subsurface coverage.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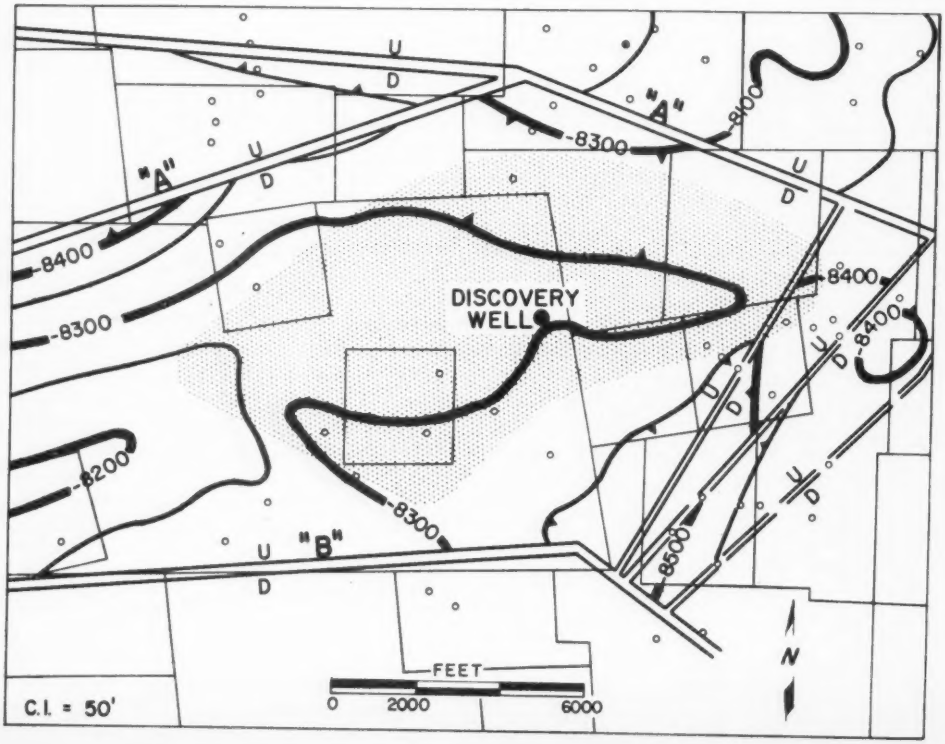
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FIG. 2. First seismic map of the Theuvenins Creek Field area contoured on the Upper Wilcox. Contour interval is 100 ft. Shaded area represents the producing area of the field.

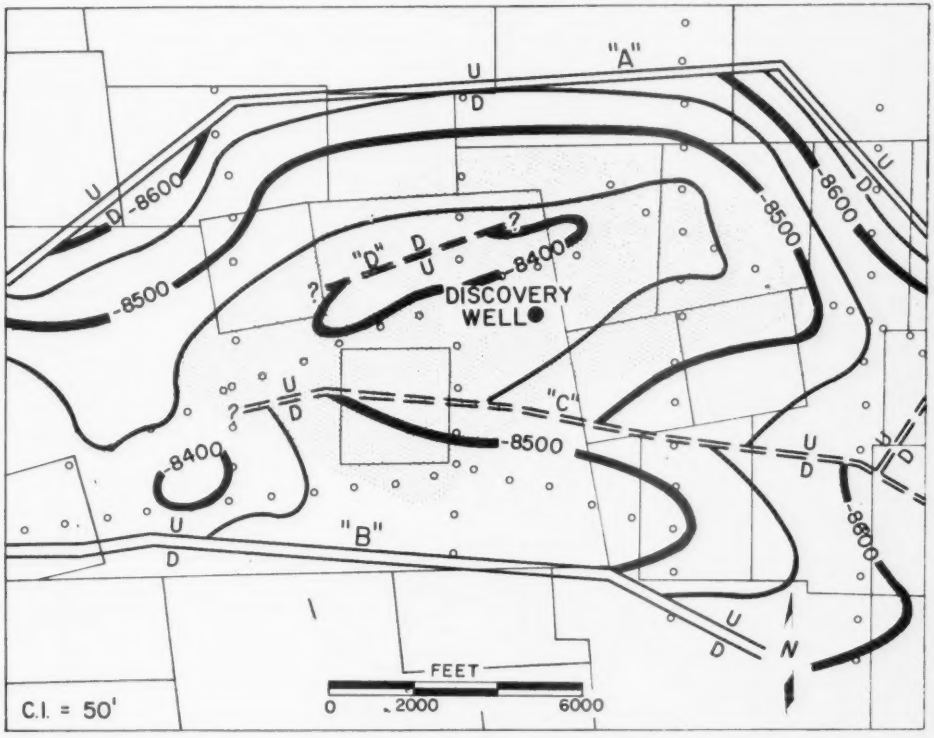

FIG. 4. Detail seismic map of Theuvenins Creek Field area. Contoured on the Upper Wilcox. Contour interval is 50 ft. Shaded area represents the producing area of the field.

Twelve traces per spread were used with 10 geophones per trace. This method yielded good quality records with the upper Wilcox reflection being an outstanding event.

From these data, the Wilcox map shown on Figure 4 was prepared. This control verified the existence of major faults *A* and *B*. An anticline was mapped between the major faults. The structure had from 150 ft to 200 ft of north dip into the downthrown side of fault *A*; it had about 200 ft of east dip and 50 ft of critical west dip. A small down-to-the-north fault *D* was mapped trending in an east-west direction and lying slightly north of the crest. The existence of this fault has been verified by subsurface control. A minor fault *C* was mapped trending east-west along the south flank of the structure. This fault was recognized as questionable in the seismic interpretation. Its existence in the subsurface has not been found.

After the completion of the detailed shooting in the area in April, 1956, Mr. L. Stanley with Sinclair Oil and Gas Company reviewed the seismic records shot by SEI. The resulting inter-

FIG. 3. Reconnaissance seismic map of Theuvenins Creek Field area. Contoured on the Upper Wilcox. Contour interval is 50 ft. Shaded area represents the producing area of the field.

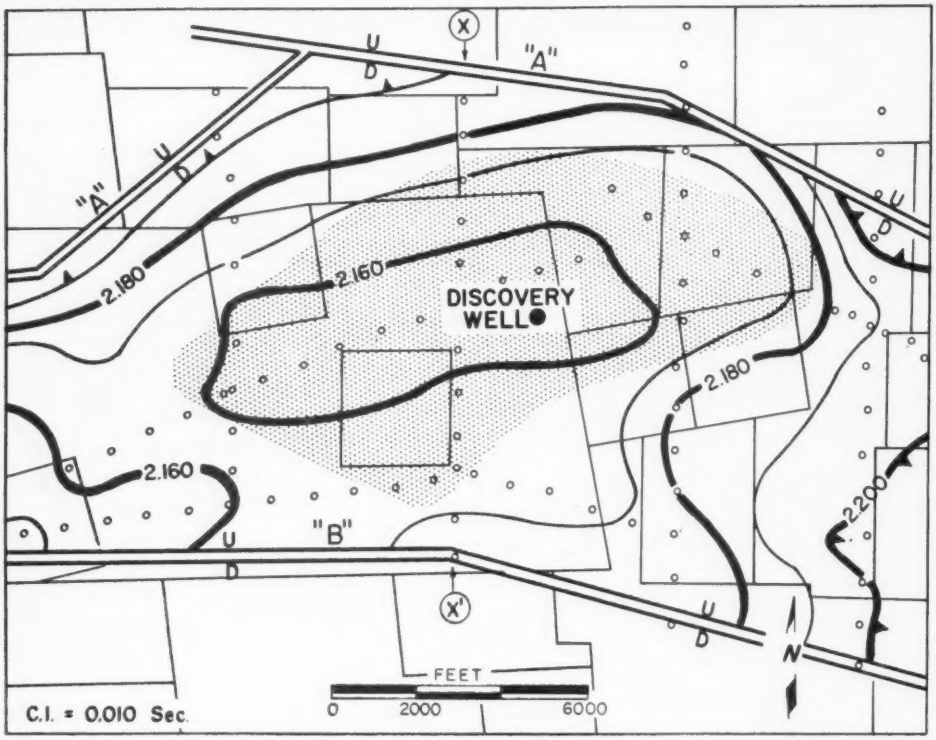

FIG. 5. Seismic review map of Theuvenins Creek Field area. Contoured on the Upper Wilcox. Contour interval is 50 ft. Shaded area represents the producing area of the field.

pretation is shown on Figure 5. The data were presented in the form of a "time" map contoured on the upper Wilcox with a contour interval of 10 milliseconds, which is about 45 ft. The stipled area outlines the present productive limits of the field.

The reviewed interpretation substantiated the existence of Wilcox structural closure with approximately 200 ft of north dip into the controlling fault, and 50 ft of critical west dip. Minor faulting was not shown on this interpretation. The small circles on Figure 5 indicate the density of shot-point control obtained in the detailed survey of 1955 and 1956. Observe the position of the north-south lines, *X-X'*, just west of the discovery well, on Figure 5. A conventional seismic record section of line *X-X'* was prepared and is shown on Figure 6.

The scale of the records in Figure 6 has been greatly reduced. The Yegua and Wilcox reflections are labeled. Due to the scale reduction, the strong north dip at the top of Wilcox is not readily apparent on the section. However, the divergence between Yegua and Wilcox may be seen as the fault north of the field is approached.

DISCOVERY AND DEVELOPMENT

After careful consideration of the seismic structural evidence and subsurface Wilcox sand conditions in productive areas along trend, Atlantic and Sinclair agreed to drill a joint test on the Theuvenins Creek structure. The Brown Fee No. 1, a 10,500 ft wildcat well, was spudded on August 15, 1957. The location was selected on the basis of seismic structural delineation. A calculated risk was taken in locating the test slightly south of the seismic crest in order to evaluate short term leases in that vicinity. The well came in structurally as anticipated. It was completed on October 12, 1957, as the discovery well of the

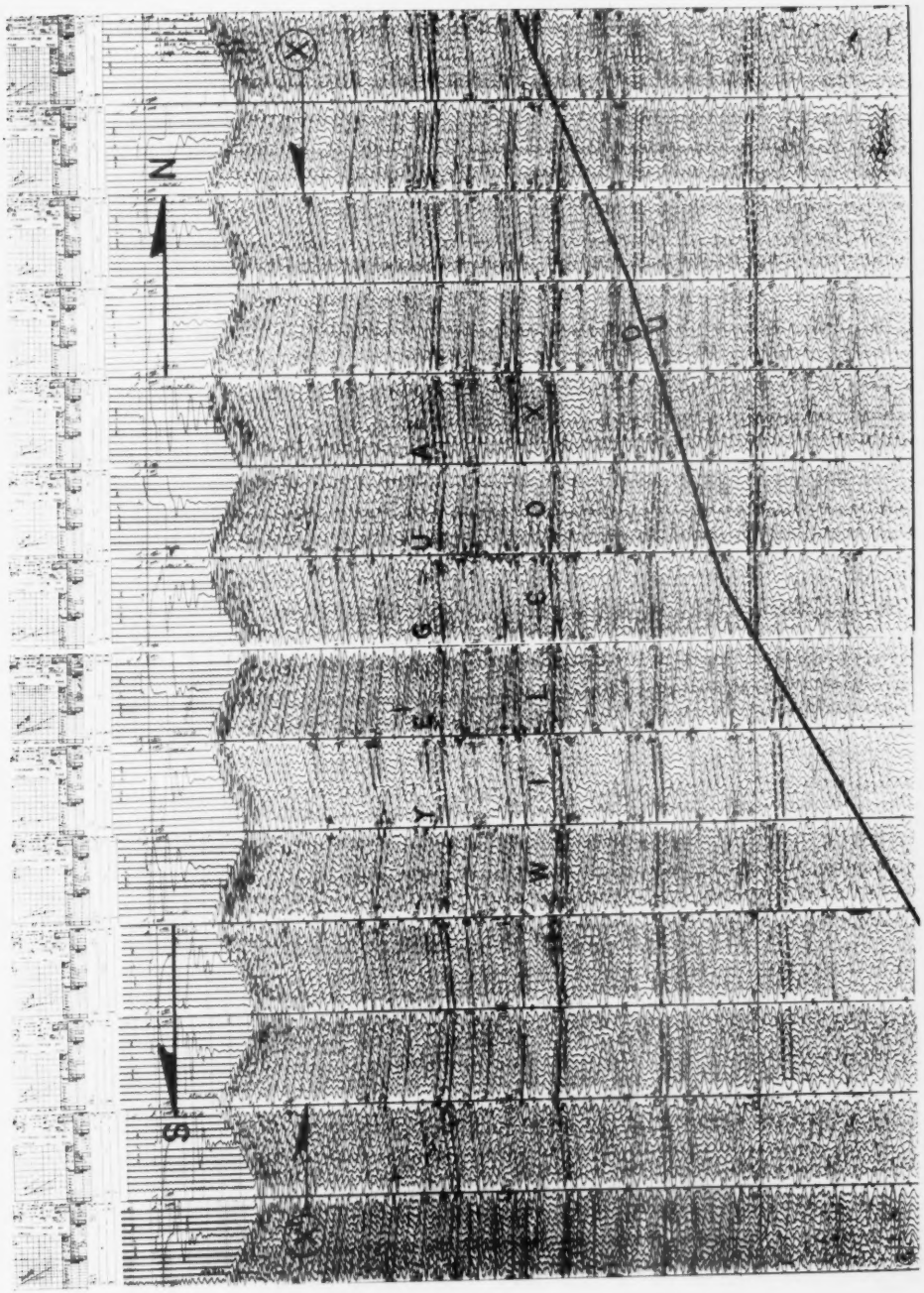

FIG. 6. Conventional record section XX' of a north-south continuous line across the crest of the Theuvenins Creek Field structure.

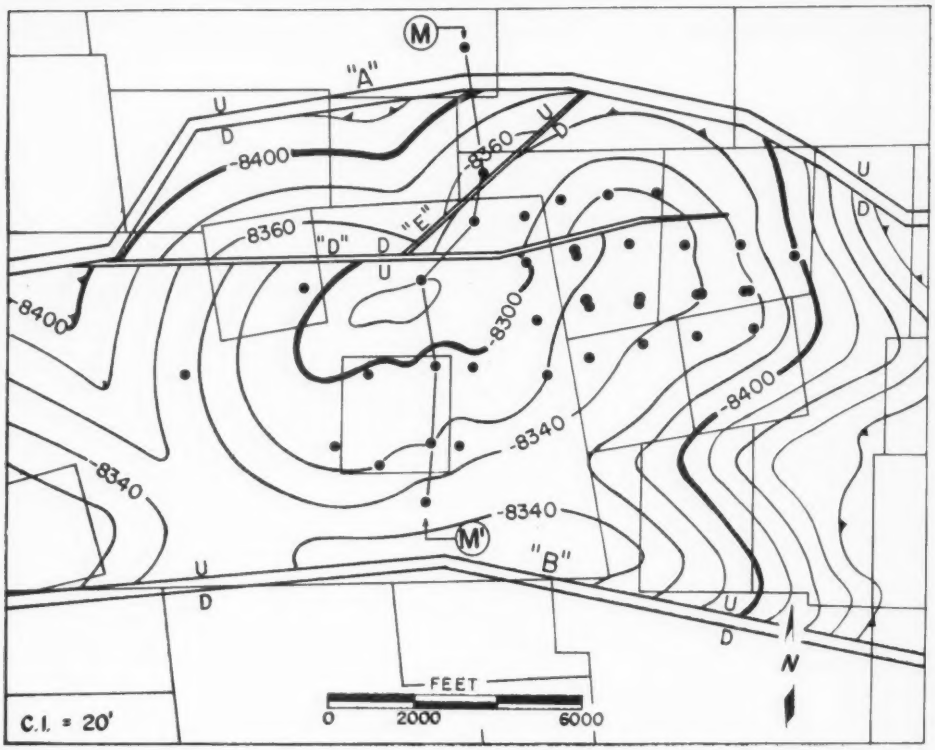

FIG. 7. Seismic-subsurface integrated map of Theuvenins Creek Field area based on seismic and subsurface data. Contoured on the 1st Wilcox Sand at an interval of 20 ft.

field. From an upper Wilcox sand the well produced 279 barrels of oil per day on a 10/64 inch choke. Gas-oil ratio was 1323-1. Gravity of the oil was 44.6, and tubing flow pressure was 1,300 pounds. Subsequent drilling developed two producing sands in the upper Wilcox.

Figure 7 shows an integrated seismic and subsurface map of the field area, contoured on the first Wilcox sand. The contour interval is 20 ft. Subsurface control conforms extremely well with the essential features of the seismic maps prepared before the structure was drilled. Fault *D* has a displacement of from 50 ft to 100 ft. A segment of this fault was mapped by SEI in their 1955–56 shooting. Fault *E* has a displacement of about 20 ft and was not found seismically. As of July, 1950, there were 38 producing wells in the field. No dry hole has been drilled on the structure.

An electrical log section was prepared, using wells along north-south line *M-M'* on Figure 7. This section is shown on Figure 8. The Sinclair-Atlantic, Brown No. 4 well in the center of Figure 8 is the highest well in the field. The first Wilcox sand is at −8,279 ft, and the second Wilcox sand is at −8,332 ft. Of the 38 wells drilled on the structure, 9 are dual producers. Thirty-one produce from the first Wilcox sand, and 16 produce from the second Wilcox sand. The net average thickness of the first and second Wilcox sands is about 10 ft each. The field has an oil column of 121 ft in the first sand and 101 ft in the second sand.

It is interesting to note on Figure 7 that the density of wells in the field is less on the western part than it is on the eastern part. The upper Wilcox sands have a tendency to shale out westward on the structure with net sand content decreasing in that direction. The 50 ft of seismic west dip is insufficient to account for the amount of oil

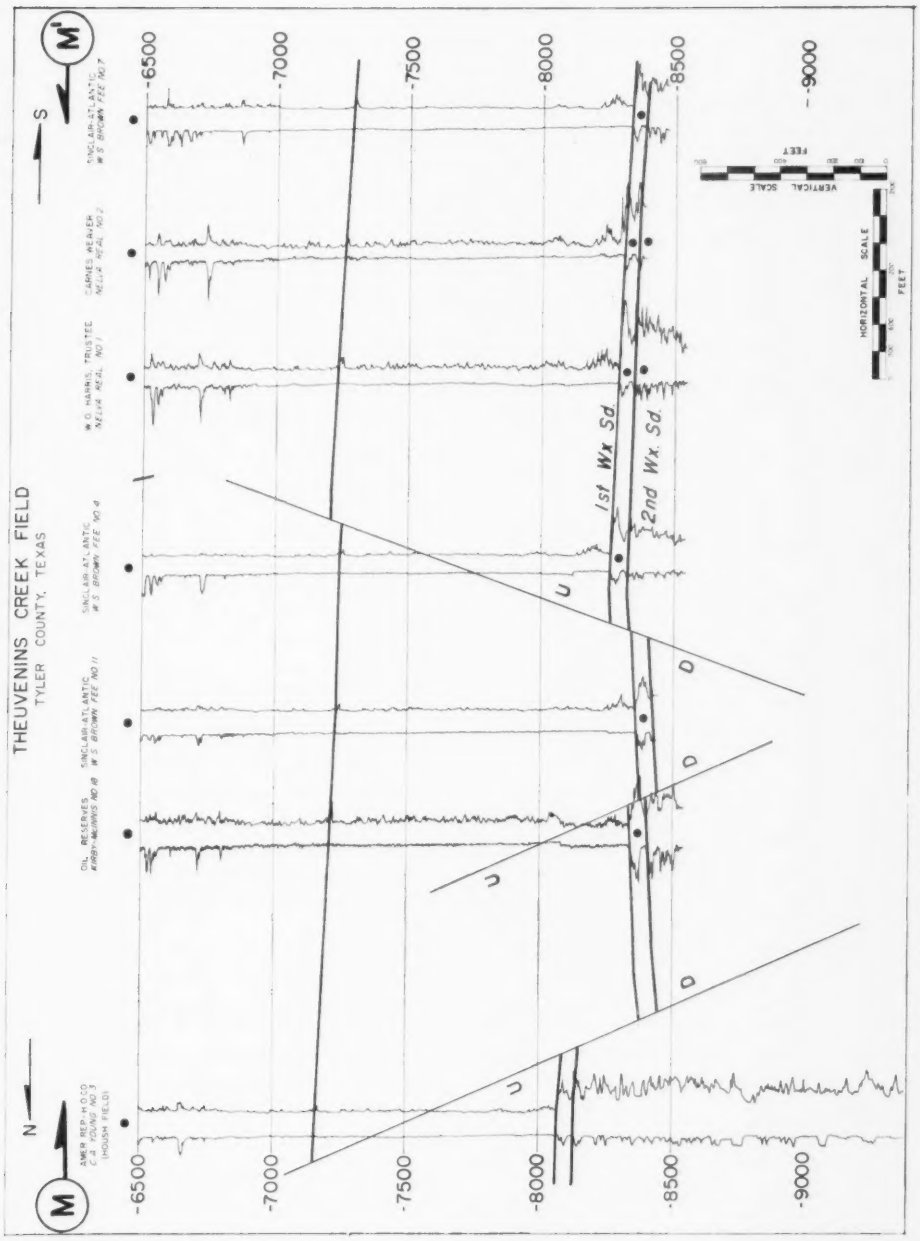

FIG. 8. North-south electrical log section MM' across the crest of the Theuvenins Creek Field structure.

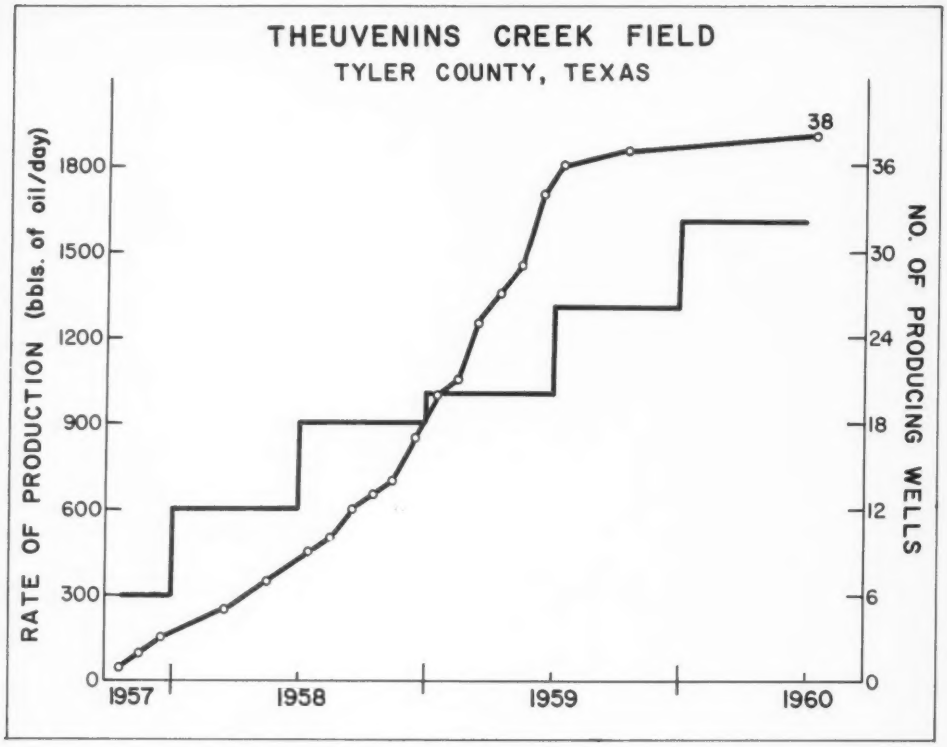

FIG. 9. Graph showing the number of wells drilled on the Theuvenins Creek Field structure and the rate of production.

column in the field. It is our belief that a shale barrier exists to the west, and has materially aided in the accumulation of hydrocarbons.

The charts on Figure 9 show field production data since its discovery. Thirty-eight producing wells were drilled as of July, 1960. Three were drilled in 1957, 14 in 1958, 20 in 1959, and one in 1960.

The steps of the chart show the daily rate of production in bi-annual segments. The early producing rate was augmented to some extent by "discovery allowable" before completion of the sixth well in the field. The rate of production was calculated on a calendar-day basis, and the decline in state-regulated producing days has limited the current productive capacity in the field. The rate of production has advanced from 300 barrels per day in 1957 to 1,600 barrels per day in 1960. To January, 1961, the total cumulative production from the field was 1.4 million barrels of oil. It is estimated that the field contains between five and ten million barrels of oil.

CONCLUSIONS

Theuvenins Creek Field is considered a major discovery for this period of exploration of the Gulf Coast land area. Its discovery should be credited to reflection seismic methods. Development drilling in the field has indicated a remarkable agreement between seismic and subsurface control. The history of the field points up the importance of obtaining adequate seismic control, necessary to satisfactorily define structures of this size that were passed up by early reconnaissance shooting.

ACKNOWLEDGMENTS

The author wishes to thank the Atlantic Refining Company for permission to publish this paper, both Sinclair and Atlantic for providing the field data, and Mr. Roy Floyd for his helpful suggestions.

GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 691–705, 11 FIGS.

GEOPHYSICAL CASE HISTORY OF THE ALTURITAS CONCESSION, STATE OF ZULIA, WESTERN VENEZUELA*

HARRY R. STENSON†

The geophysical case history of Alturitas area, western Venezuela is presented. It is unusual in that all the commonly used geophysical methods were employed. The Alturitas anomaly was discovered by the torsion balance in 1929. Subsequent surveys included the gravity meter, magnetometer, refraction and reflection seismograph. The surveys are discussed in chronological order giving the reasons for the particular surveys and results obtained.

Although the geophysical results were generally good, an error in correlation led to a misinterpretation of stratigraphic relations. This in turn resulted in drilling depths much deeper than anticipated. Five wells were drilled on the concession resulting in three oil wells and two dry holes. Alturitas-1 and Alturitas-2 are two of the deepest oil wells outside the United States. Maps are presented for the key geophysical surveys.

INTRODUCTION

The geophysical history of the Alturitas concession spans a period of approximately thirty years. During this interval the concession was explored by gravity, magnetic, and seismograph methods. Three of five wells drilled to this date were completed as oil wells and two were dry holes. Only that phase of the exploratory effort devoted to geophysics is presented here. Other exploration tools, especially surface studies and photo mapping, were equally successful in determining structure at Alturitas. These latter findings are not discussed in this paper.

LOCATION AND HISTORY OF THE ALTURITAS CONCESSION

The Alturitas concession (Figure 1) is located in the state of Zulia, western Venezuela near the Colombian-Venezuelan border and along the eastern flank of the Perijá mountain range. The concession is 30 km (18.6 miles) west of the prolific oil fields of Lake Maracaibo and along a northeast-southwest trend of producing anticlinal structures. The concession in its present form was obtained under The Venezuelan Petroleum Law of 1943–45 and consists of 35,500 hectares (87,685 acres).

In the late twenties and early thirties much of the acreage between Lake Maracaibo and the Perijá mountains was held by private citizens of Venezuela under mining laws of the early nineteen hundreds. Many of these leases were later sold to foreign capital. The impetus that brought this capital into Venezuela took place in December of 1922 when Shell's Los Borrosos-2 (La Rosa field) blew out and flowed at the rate of 100,000 barrels of oil per day. More than fifty companies were attracted to Venezuela in hopes of similar success. One of the companies with leases west of Lake Maracaibo was the Creole Petroleum Corporation. Other concessionaires in the general Alturitas area were Venezuela Gulf Oil Company, Venezuelan Pantepec Company, Falcón Oil Corporation, Esperanza Petroleum Corporation, Union National Petroleum Company, Lago Petroleum Corporation, Texas Company, and others. As a result of mergers and renouncements there are five companies holding concessions west of Lake Maracaibo. These companies are Shell, Richmond, Mene Grande, Compañía Española de Petróleo, S. A., and Creole.

1929 TORSION BALANCE SURVEY

The Creole Petroleum Corporation of Delaware initiated a broad torsion balance reconnaissance survey in the year 1929. The purpose of the survey was to explore the entire area west of Lake Maracaibo in hopes of locating structures similar to the Mara and La Paz fields to the north. The torsion balance, a new exploration tool in Ven-

* Presented at the January 9, 1961 meeting of the Asociación Venezolana de Geofísica in Caracas.

† Creole Petroleum Corporation, Caracas, Venezuela.

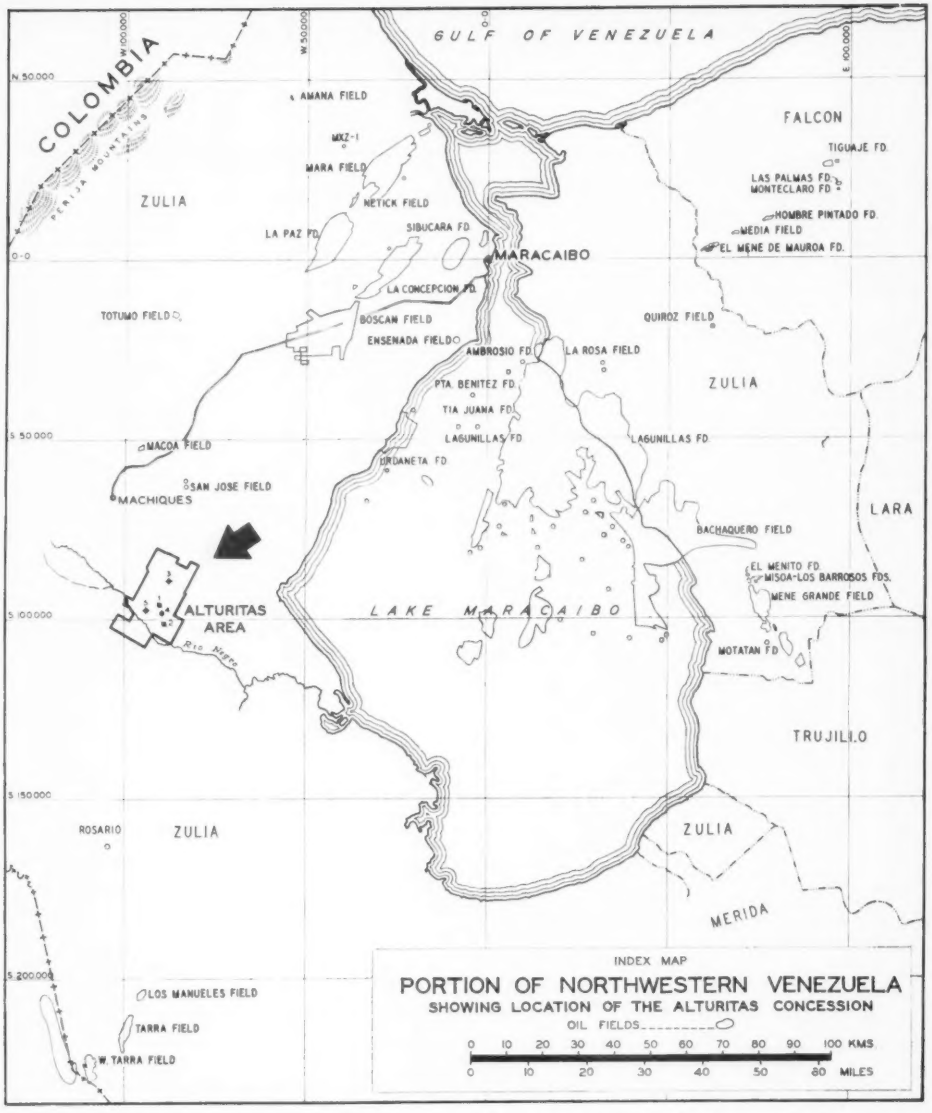

FIG. 1. Index map of a portion of northwest Venezuela showing location of the Alturitas concession. Outline of concession shown on all figures is that of present day concession.

ezuela, successfully located several gravity anomalies. One anomaly was at Alturitas where Creole had several leases. Figure 2 shows that portion of the 1929 torsion balance survey covering the present day concession. The anomaly was described as a double crested anticline with two main axes, having a length of 30 km (18.6 miles) and a width of 5 to 12 km (3 to 7 miles). The gravity anomaly was given the name Alturitas from a ranch by that name at the site where the

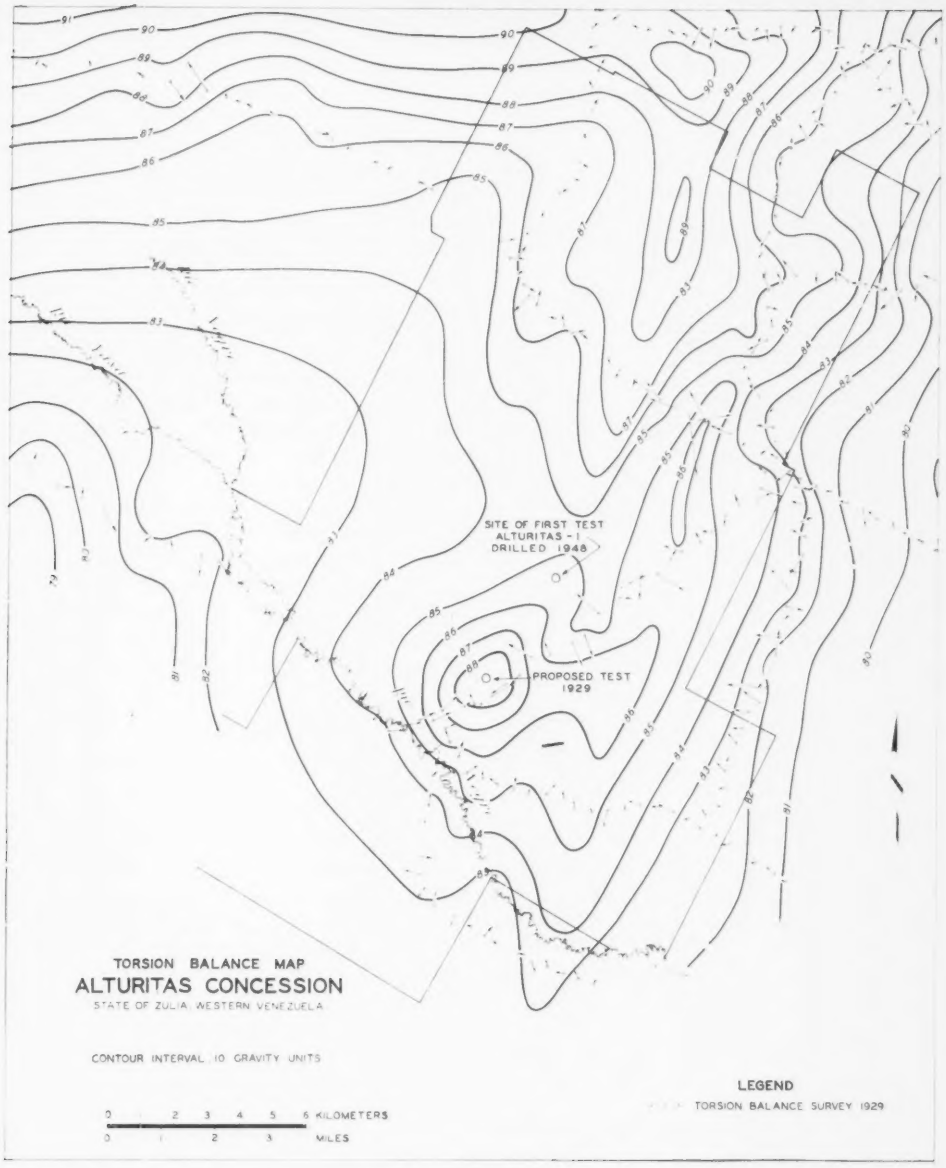

FIG. 2. Portion of the 1929 torsion balance map showing location of a proposed test based on this map and site of Alturitas-1 drilled in 1948.

Río Negro crossed the axis of the anomaly. The torsion balance map shows the gradients and also the gravity intensity in contour form. It is interesting to note that a location was proposed in 1929 just a few kilometers southwest of the Alturitas-1 test made nineteen years later. It was

stated in 1929 that the best prospective oil zone (Frontal Sandstone-Upper Eocene) was probably beyond the reach of the drill, but because of the prominence of the structure there might be oil in higher zones. Notwithstanding the limited amount of torsion balance data, a very optimistic prediction was made as to the size of the structure. The structure was stated to have an amplitude of 2,800 to 3,000 ft (actual amplitude is about 1,900 ft) and the closure calculated at the main anomaly to be 600 ft (actual closure is about 800 ft). Shown on the torsion balance map is the location proposed in 1929 and the location of Alturitas-1 drilled nineteen years later.

1930 MAGNETOMETER SURVEY

In 1930 three lines of magnetometer stations were run across the Alturitas anomaly. These data were a portion of a reconnaissance magnetometer survey of the Maracaibo basin. The survey lines were limited to and extended over the anomaly indicated by the torsion balance work. Because of the sparseness of these data, no attempt was made to draw a contour map. The results of this survey were presented in the form of magnetic profiles along the lines of stations observed by the torsion balance. These very limited data, although not conclusive, tended to eliminate the possibility of a granite or basement core underlying the area at shallow depth.

1933 RECONNAISSANCE REFRACTION SEISMOGRAPH SURVEY

In 1933 a reconnaissance refraction seismograph survey was conducted over a large portion of the Maracaibo basin. As a part of this survey, three refraction lines were shot over the torsion balance anomaly at Alturitas. From the refraction work, the axis of a seismic high was interpreted to be from 5 to 10 km west of the principal anomaly with fairly uniform east dip through the area of the gravity anomaly. The refraction data also indicated a depth of about 6,500 ft to the Eocene in the area of the gravity maximum, whereas previous torsion balance estimates had indicated nearly twice that. It was recognized from the torsion balance survey that insufficient data had been obtained to cover the west flank of the gravity anomaly. It was also recognized that the topography was unfavorable for the best torsion balance results. Nevertheless, it was stated that no reasonable gravity correction could shift the torsion balance anomaly far enough from its observed position to make it coincide with the seismic axis. Although there was a difference of 5 to 10 km in axial position of the anomaly, as derived from the two types of data, the refraction results were useful. The relatively high velocity recorded could be considered as evidence that the Eocene formation (Frontal Sandstone) was not as deep at Alturitas as originally suspected.

1936 RECONNAISSANCE REFLECTION SEISMOGRAPH SURVEY

In 1936 the first reflection work was carried out. The survey was completely reconnaissance in nature and consisted of four reflection lines across the anomaly. It was hoped that this small amount of data would fix the axis of the Alturitas structure, but the results were inconclusive since energy return was very poor. A dip map made by combining both the refraction and reflection data was unsuccessful in confirming the axial position of the Alturitas anomaly. Insufficient energy return and insensitive recording instruments probably contributed to the poor results obtained, as the reflecting horizons were much deeper than the resolving power of the instruments.

1937 TORSION BALANCE SURVEY

Since doubt still existed as to the location of the axis of the anomaly, a limited torsion balance survey was made in 1937 to check the 1929 original data. Particular stress was placed upon locating the exact position of the axis. Four lines of stations were run along the same lines previously used by the seismograph. The 1937 survey was in very close agreement with the 1929 work at every point where the two surveys intersected. A composite map drawn from data of the two surveys showed no appreciable difference from the one shown in Figure 2.

1947 DETAILED GRAVITY SURVEY

During the period 1943–45, Creole consolidated its holdings in Alturitas and immediately thereafter started an extensive exploration program to evaluate the acreage. The discovery of new Cretaceous reservoirs in the Mara and La Paz fields, in Richmond's Zulia 26-1, and the West Tarra field, renewed interest in Alturitas. The concession was along the same trend as these new discoveries. A stepped-up geophysical program

calling for detailed gravity, magnetic, and seismograph work was started on December 18, 1946.

The existence of the Alturitas torsion balance anomaly was yet to be confirmed by modern geophysical tools. A gravity meter survey was, therefore, programmed to check the old torsion balance picture. It was realized that the topography was extremely rough for torsion balance measurements and that the area required coverage by a method, such as the modern gravity meter, whose measurements were less affected by topography. With a lack of knowledge of the extent to which the torsion balance was affected by terrain, it was impossible to draw reliable conclusions about the anomaly or its causative. It was also considered that the new gravity interpretation would offer more reliable control for the placing of seismic lines.

Figure 3 is a Bouguer gravity map of the 1947 survey. The main feature of the map is the large north-south trending anomaly extending across the concession. Superimposed on the Bouguer map is the principal torsion balance anomaly. Note that the torsion balance anomaly is mapped slightly to the southwest of the Bouguer anomaly, indicating that the earlier torsion balance work was more accurate in determining the location of the feature than the limited amount of weak seismic data. It was recognized that an anomaly of such magnitude might be caused by several geological conditions. Four of the more likely possibilities were: (1) Intrabasement effects, (2) Basement topography, (3) A structural and/or topographic feature at considerable depth, (4) A structural and/or topographic feature at a shallow depth.

Calculations determined the maximum possible depth to the causative structure or effect at 11,500 ft. It was emphasized that this was the maximum depth to the top of the causative effect and that a structure could lie at any depth above this. Conclusions drawn from the gravity interpretation were that the anomaly must be the result of structure in the sedimentary section and/or a topographic feature on an unconformity surface. This precluded either intrabasement or basement surface effects. Also, since geological studies predicted considerably more than 11,500 ft of sediments in the area, the structure must lie within this range. The limited amount of earlier magnetic data also indicated the basement to be at considerably depth. Finally, the early refraction data may have given a slight clue to a deep basement in Alturitas. Figure 4 is a comparison of gravity profiles from the 1929 and 1937 torsion balance surveys and the 1947 gravity meter survey.

1947 DETAILED MAGNETOMETER SURVEY

It had been planned to run both the gravity and magnetic surveys at the same time, but the equipment for the magnetic work was not available. The latter survey was, therefore, begun shortly after the completion of the gravity survey. The purpose of the magnetometer survey at this time was twofold: (1) The survey might offer additional evidence as to the depth to basement rock. (2) The work would serve as an evaluation of this method of geophysical prospecting since this was one of Creole's first detailed magnetometer surveys.

The 1947 survey employed most of the engineering data and stations obtained by the gravity meter survey. Figure 5 is a vertical magnetic intensity map drawn on these data. The survey did not reveal any sharp local anomalies indicative of shallow basement. It also ruled out the possibility of the Alturitas anomaly being intrabasement in origin since there was no correspondence of a magnetic anomaly with the large gravity anomaly. The magnetic map shows moderate gradients and lack of sharp anomalies, which characterize an area of deep basement. The sharpest magnetic gradients are located in the same general area as the gravity anomaly, but no marked magnetic trend was indicated. It was interpreted that these gradients originated in the sedimentary section, even in the near-surface section, due to differential weathering.

1947 DETAILED REFLECTION SEISMOGRAPH SURVEY

The detailed reflection seismograph survey began on July 8, 1947. The purpose of this survey was as follows:

(1) to check the large gravity anomaly discovered by the torsion balance in 1929 and confirmed by the gravity survey in 1947;
(2) to gain a better idea of the total thickness of sediments present and the age of these sediments, if possible, in advance of the drill;
(3) to map in detail the faults which were known to exist from earlier gravity data; and

FIG. 3. 1947 Bouguer gravity map comparing position of principal torsion balance anomaly to gravity anomaly.

(4) to provide sufficient drilling locations for proper evaluation of the concession.

No difficulties were experienced in the field operations of this survey. Conventional split spreads were used and time sections were plotted for all lines. In the Alturitas area proper, only one consistent band of reflections could be mapped. Figure 6 is the interpretation of these data in the form of a reflection time map. The survey confirmed the gravity picture at Alturitas and indicated the presence of a large north-south anti-

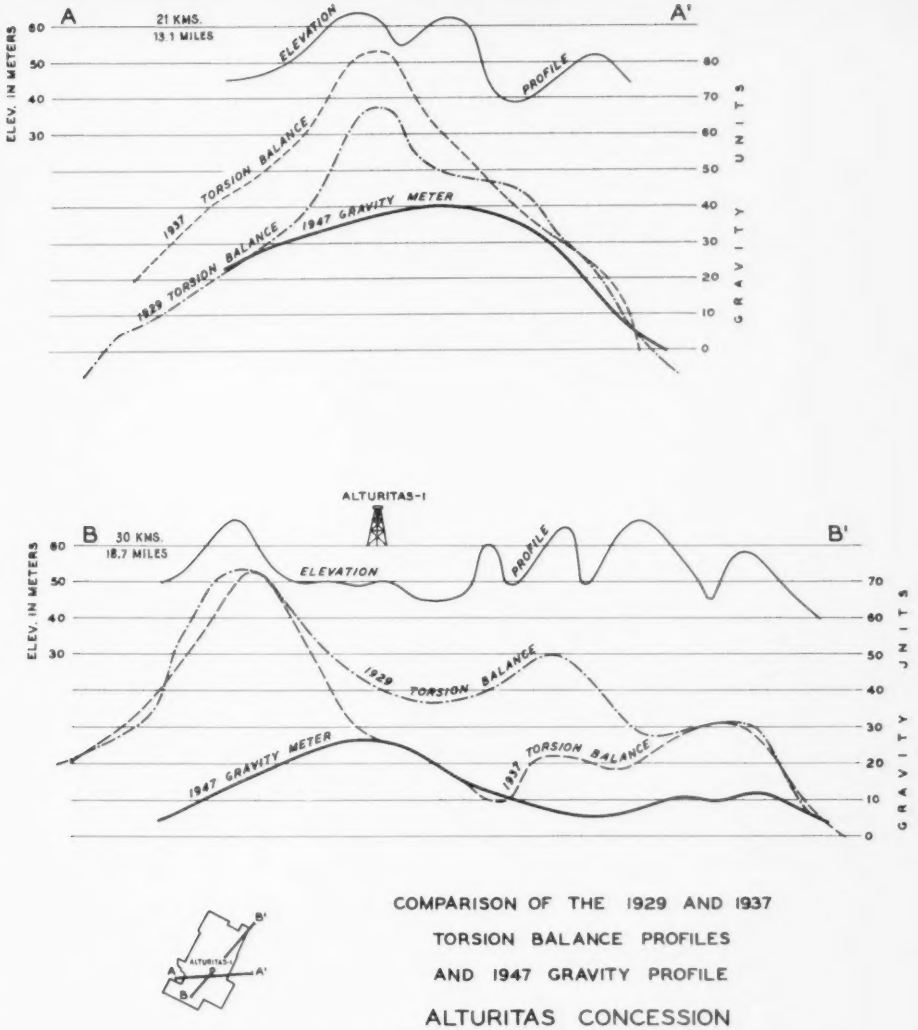

FIG. 4. Comparison of 1929 and 1937 torsion balance profiles and 1947 gravity profile. Note the alignment of torsion balance anomalies with the topographic high.

cline that covered most of the concession. Several faults, generally with a north-south trend, complicate both the eastern flank and northern part of the structure.

With confirmation of structure at Alturitas there remained the question of identifying the stratigraphic position of the reflecting horizon and its depth over the structure. Since no deep subsurface information was available in the immediate area, the following conjectures were made as to the geologic age and depth to the reflecting horizon:

(1) The reflection must have originated from a zone of pronounced lithologic change, specifically a limestone in contact with a shale or sandstone. The uppermost limestone to outcrop in the foothills to the west was the Socuy member of Cretaceous age. The presence of this limestone in

FIG. 5. 1947 magnetometer map of the Alturitas concession.

the foothill area, and the fact that it was a strong reflecting source in other areas of western Venezuela, gave considerable weight to calling the Alturitas reflection Cretaceous in origin.

(2) In 1948, just prior to the drilling of Alturitas-1, Creole shot several reconnaissance lines north of the Alturitas concession (Figure 7). Although these lines were shot for other reasons, it was hoped that these data would aid in the identification of the Alturitas reflection by tying it to known subsurface data from the recently completed Richmond wells Z-25-1 and Z-26-1,

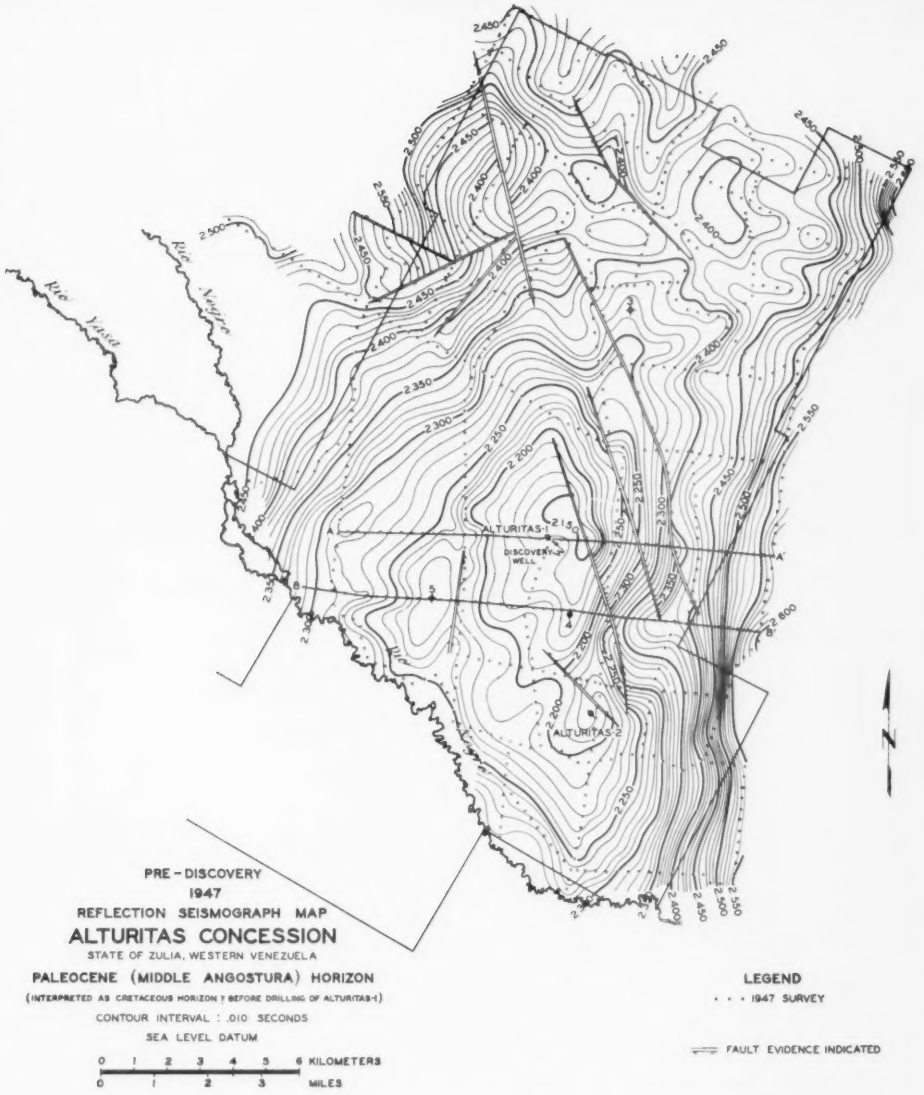

FIG. 6. 1947 reflection seismograph map used to select first two exploratory tests Alturitas-1 and Alturitas-2.

located 32 km (20 miles) to the north. The index map of Figure 7 shows the position of the seismic lines with respect to the concession, the outcrop area, and wells Z-25-1 and Z-26-1. The interpreted cross-section along seismic line *C-C'* is also shown on Figure 7. The most prominent reflection in the Z-25-1 and Z-26-1 area was tied to the Cretaceous in both wells and carried south where it tied to the single reflection at Alturitas. It was stated, although the reconnaissance data did not definitely establish the stratigraphic position of the reflector mapped in Alturitas, that it was probably Cretaceous in origin based on the correlation of the well information to seismic data.

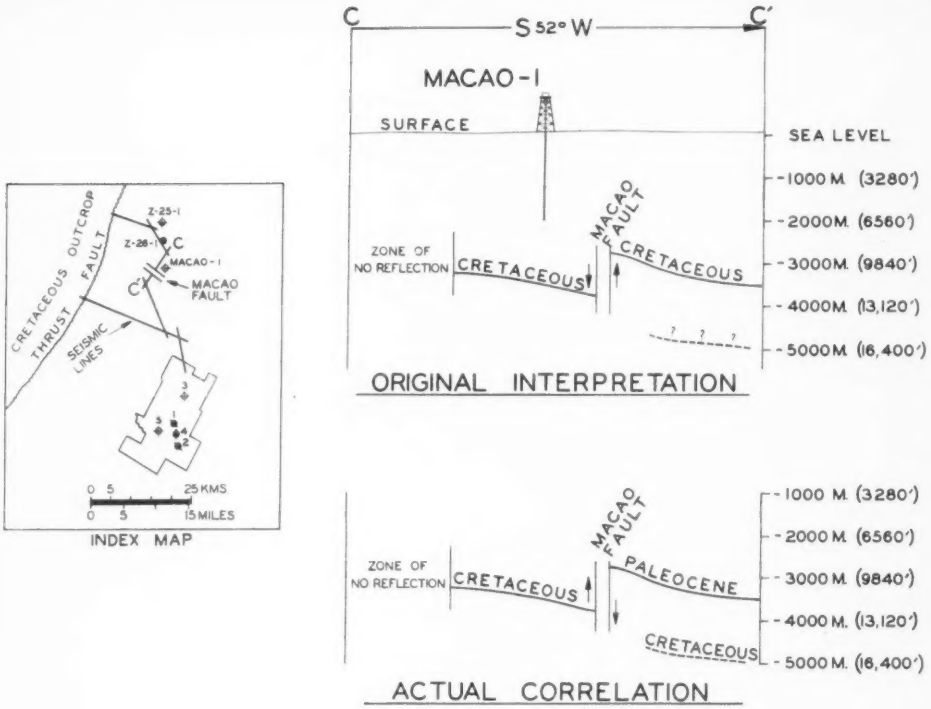

FIG. 7. Generalized cross-section showing original interpretation across the Macoa fault and the actual condition.

Age	Formation	Thickness Alturitas – 1
Miocene	La Villa Los Ranchos	3,670′
Miocene-Oligocene	El Fausto Group	5,151′
Eocene	La Sierra	892′
Paleocene	Angostura Group	2,493′
Cretaceous	Mito Juan Colon Socuy La Luna Capacho Apon	4,829′
Triassic-Jurassic	La Quinta	?

FIG. 8. Generalized stratigraphic chart of the Alturitas concession as taken from Alturitas-1.

(3) The predicted depth to the Cretaceous Socuy formation based on limited velocity information and projection of the known outcrop section to Alturitas gave a depth of 11,500 to 12,000 ft over the structure.

(4) Calculations of gravity data determined a maximum depth of 11,500 ft to the top of the effect causing the anomaly, in the same depth range as the Socuy limestone projections.

The seismograph map (Figure 6) was used to pick the first two exploratory tests of the concession. The first location, Alturitas-1, was near the highest point on the axis of the structure and on the upside of a sizeable fault. The well was spudded December 14, 1948. Since the strong reflection was thought to originate from the Cretaceous Socuy limestone, a total depth of 13,000 ft was projected to test the entire sedimentary section. The well drilled to a depth of 17,039 ft before it penetrated the complete

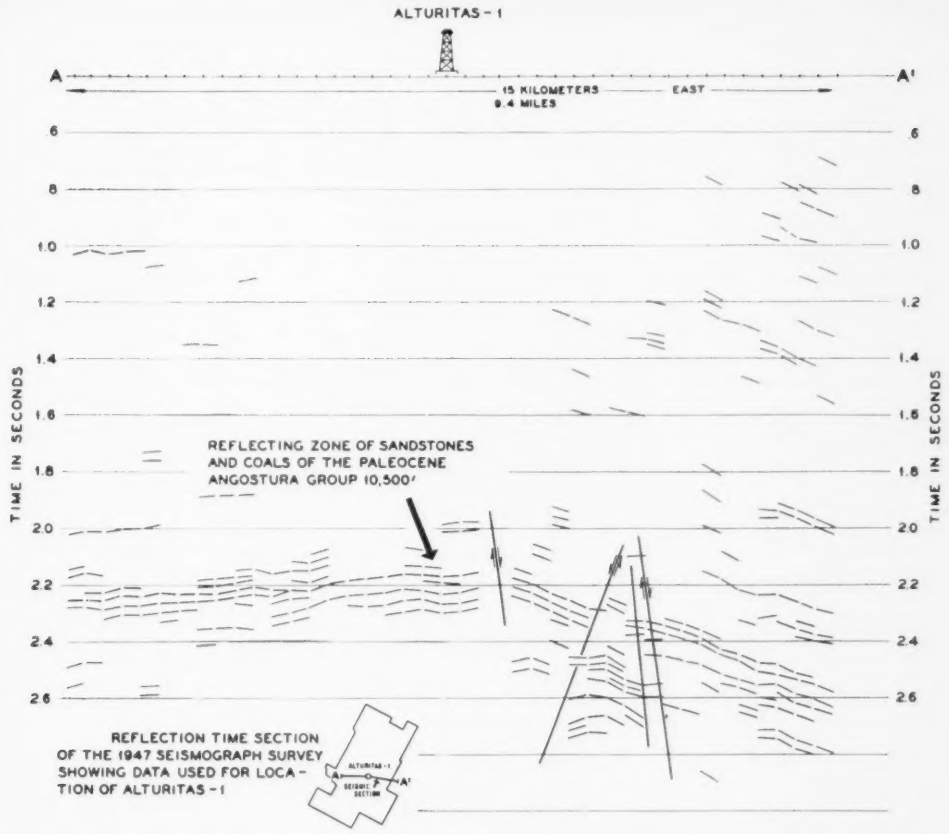
ALTURITAS - 1
A
A'
15 KILOMETERS
9.4 MILES
EAST
TIME IN SECONDS
REFLECTING ZONE OF SANDSTONES AND COALS OF THE PALEOCENE ANGOSTURA GROUP 10,500'
REFLECTION TIME SECTION OF THE 1947 SEISMOGRAPH SURVEY SHOWING DATA USED FOR LOCATION OF ALTURITAS - 1

FIG. 9. Reflection time section from the 1947 seismograph survey showing data used for location of Alturitas-1. Strong reflecting band was interpreted as Cretaceous (Socuy) before drilling of Alturitas-1. See Figure 6 for exact location of Profile *A-A'*.

column. Figure 8 shows the stratigraphic section penetrated and the thicknesses encountered. Figures 9 and 10 represent typical reflection time sections across the Alturitas structure.

Alturitas-1 encountered saturated oil sands in the Basal Eocene La Sierra formation and the Paleocene Angostura Group (Angotsura Group, as discussed in this paper, has been replaced by the Guasare, Marcelina, and Mirador formations). Good shows were also obtained in the Cretaceous section. The basal 30 to 40 ft of sandstone in the Angostura Group was a prolific producer, flowing up to 1,770 barrels per day of 20.4° API gravity oil. The Middle Angostura tested 470 barrels a day of 20° API gravity oil. Sands of the Upper Cretaceous Mito Juán formation were interpreted as being noncommercial. Tests of the Cretaceous limestone indicated the presence of 34° to 36° API gravity oil, but mechanical difficulties prevented an entirely satisfactory test in this section. The Basal Eocene sand was not tested.

It was evident after the drilling of this deep test that the strong reflection observed in Alturitas was not from the Cretaceous limestone, but from a series of coal beds of the Paleocene Middle Angostura Group approximately 4,000 ft higher in the section. These coal beds are easily recognized on both the continuous velocity log and electric log. Figure 11 shows a portion of the continuous velocity log from Alturitas-4, demonstrating the low interval velocities obtained from this Paleocene section.

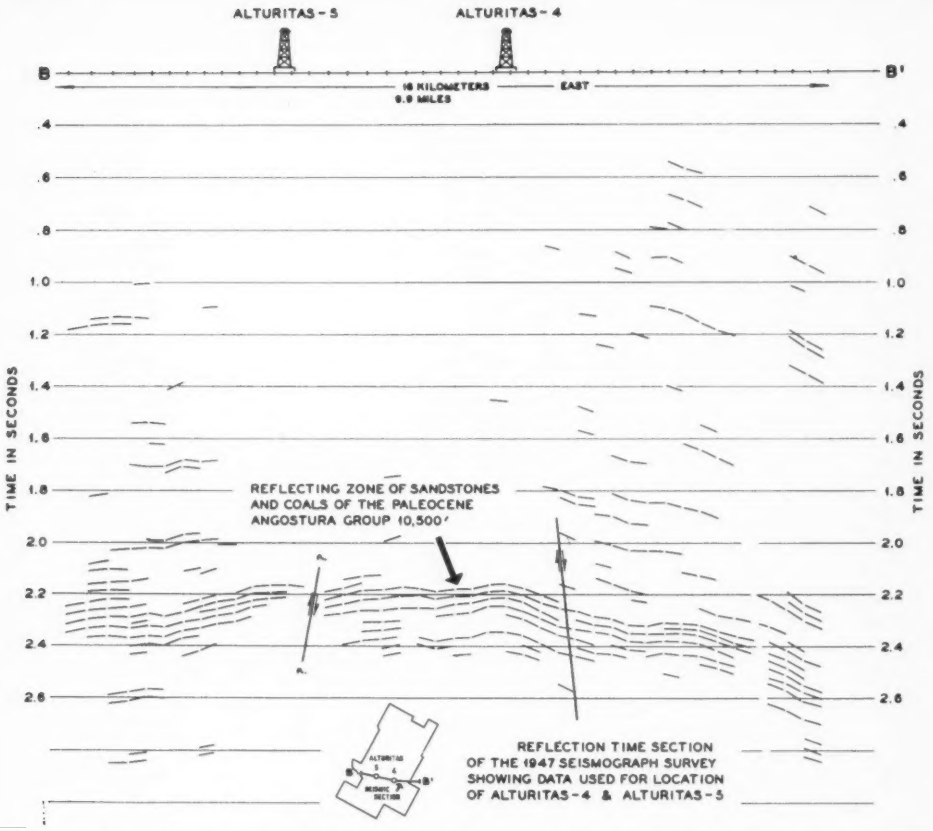

FIG. 10. Reflection time section from the 1947 seismograph survey showing data used for location of Alturitas-4 and Alturitas-5. See Figure 6 for exact location of Profile *B-B'*.

The question was immediately raised as to how the miscorrelation came about since there was a subsurface tie to Z-25-1 and Z-26-1. Since most records had only one reflection band, no interval could be established to support correlation from seismogram to seismogram, especially across faults. Just south of Macoa-1 (Figure 7) a fault of 3,500 to 4,000 ft had been interpreted as down to the north. It was stated by the interpreter that the correlation at this point was very questionable and that the fault could actually be downthrown to the south based on a few questionable deeper reflections located just south of the fault zone. A restudy of these data revealed that the fault was actually downthrown to the south with the original interpretation correlating the Cretaceous reflection to the north and the Paleocene reflection to the south across the fault. This reflection (Paleocene) was then carried south to Alturitas in the belief that it was Cretaceous. The error in correlation helped substantiate previous reasoning for calling the reflection at Alturitas Cretaceous in origin. Further seismic studies and subsurface data indicate that the coal beds in the Alturitas area are of sufficient thickness to serve as a velocity interface, whereas to the east and north these beds are probably faulted-out, thin-out, or change facies and do not serve as a reflecting horizon. It is currently interpreted that the Paleocene coal beds are of insufficient thickness to serve as a reflector north of the fault at Macoa. The predominant reflection is Cretaceous as designated, but south of the fault the Paleocene coals give rise to the predominant

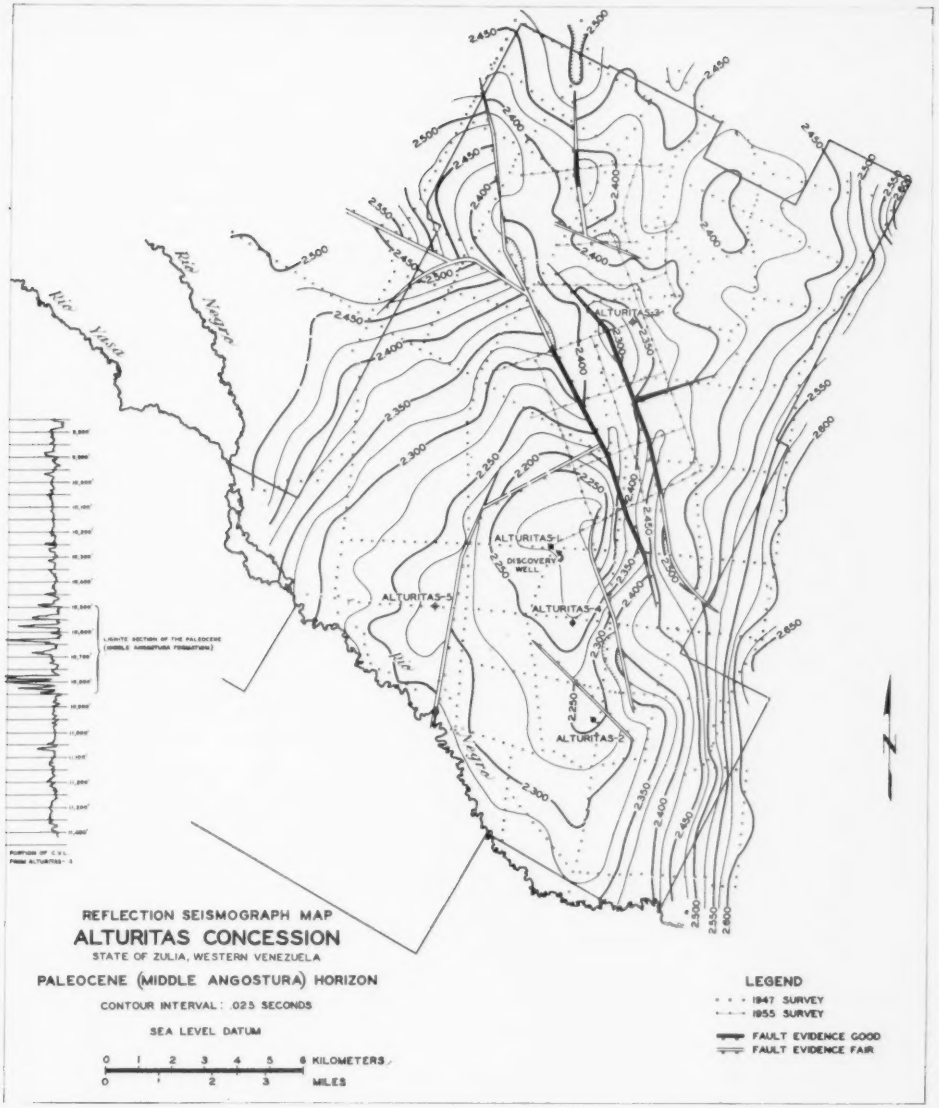

FIG. 11. Composite reflection seismograph map from the 1947 and 1955 surveys used to select locations Alturitas-3, Alturitas-4, and Alturitas-5. Also shown is a portion of the CVL log from Alturitas-4 demonstrating the low velocity (7,200 ft/sec.) of the Paleocene coal beds compared to adjacent sediments (13,000 ft/sec.)

reflecting horizon. The seismograph map, therefore, actually represents a stratigraphic position 4,000 ft higher in the section than originally interpreted.

Probably too much emphasis was given to the maximum depth figure of 11,500 ft (depth to gravity effect). It was clearly stated that the effect causing the anomaly could be higher in the sedimentary section. But the coincidental fact that both the limited velocity data and projection

of known stratigraphic thicknesses also arrived at a figure of 11,500 to 12,000 ft provided much weight to the belief that the reflection and density contrast were from the same source. The maximum depth calculation can be shown to fit only an extremely sharp structure. Since the actual structure as mapped by the seismograph is rather broad, the density contrast causing the gravity anomaly was obviously higher in the sedimentary section than the Cretaceous.

Alturitas-2 was drilled in 1952 to evaluate the productive area of the concession further, especially the Cretaceous sands and limestones. As previously mentioned, mechanical failures had prevented a thorough testing of these Cretaceous zones in Alturitas-1. The well drilled to a total depth of 17,265 ft. The lithology of the sediments in Alturitas-2 was similar to that found in Alturitas-1 and most tops were structurally lower by less than 100 ft. Alturitas-2 flowed 100 barrels of oil a day from the Basal Eocene La Sierra formation and 310 barrels a day from the Basal and Middle Angostura Groups. The well also tested 121 barrels a day in the Upper Cretaceous Mito Juán formation and 450 barrels a day from the Upper and Middle Cretaceous limestone. These amounts could probably be increased by pumping.

1955 SUPPLEMENTAL REFLECTION SEISMOGRAPH SURVEY

In 1955, Creole made an additional seismograph survey in the north-central portion of the concession for the purpose of locating a third deep test to evaluate the more complicated northern flank of the structure. It was realized that the grid pattern of the previous survey was too large for detailed mapping of the complicated fault system. The purpose of the 1955 survey was to provide closer control on the faults before the third location was made. The additional data resulted in major changes with respect to the direction of throw on the faults along the northern and eastern flanks of the structure. Figure 11 is a composite map of both the 1947 and 1955 shooting contoured on the Paleocene Middle Angostura horizon. This map was used to select locations Alturitas-3, Alturitas-4, and Alturitas-5. Although no new data were involved in the vicinity of locations Alturitas-4 and Alturitas-5, a thorough review was made of these data before the locations were made. The 1955 data are shown by connected shotpoints. These data were recorded on magnetic tapes and were generally of fair to good quality. A major change in interpretation was made with respect to the two northwest-southeast trending faults that separate Alturitas-1 from Alturitas-3. The original 1947 seismic map shows the elongated fault block to be a horst while the later interpretation shows the block as a graben. On both maps the location of Alturitas-3 is on a seismic high with closure against a fault.

Alturitas-3 was projected for 13,000 ft but the well was abandoned at a depth of 12,542 ft due to mechanical difficulties. The objectives were only partially fulfilled since the well did not test the prolific basal sand of the Angostura Group as found in Alturitas-1. There were only slight traces of oil in the Basal Eocene La Sierra formation and all other sands in the Paleocene Angostura Group were wet. The well was abandoned as a dry hole.

Alturitas-4, located midway between Alturitas-1 and Alturitas-2, drilled to a total depth of 11,402 ft and found the Basal Eocene La Sierra sands saturated with medium gravity oil.

Alturitas-5 was drilled along the western flank of the anticline and on the upside of a north-south trending fault which separates the well from the Alturitas-1, -2, and -4 reservoir. Alturitas-5 drilled to 12,183 ft. After three tests in the Basal Eocene La Sierra, and only slight shows in the Paleocene Middle Angostura, it was abandoned as a dry hole. The well did not penetrate the lower Angostura or Cretaceous section.

SUMMARY AND CONCLUSIONS

(1) A gravity anomaly was discovered at Alturitas by the torsion balance method in 1929.

(2) The geophysical phase of exploring the Alturitas concession is probably complete. Subsurface data from five wells confirm the structure mapped by the seismograph.

(3) Subsurface data now on hand indicate that the Paleocene coal beds of the Middle Angostura formation are a phenomenon peculiar to the Alturitas area. In this zone the beds have sufficient thickness to serve as a velocity interface which gives a prominent band of reflections.

(4) The concession has been partially evaluated by the drilling of five deep exploratory tests.

Mechanical difficulties prevented a complete test of all prospective zones. Alturitas-1, the discovery well, and Alturitas-2 penetrated the entire post Jurassic-Triassic section. These two wells, along with Alturitas-4, were drilled along the crest of the anticline as mapped by the seismograph. The wells discovered substantial oil sections in the Basal Eocene, Paleocene, and Cretaceous sediments.

ACKNOWLEDGMENTS

The writer expresses his appreciation to Creole Petroleum Corporation for permission to compile and publish these data, also to members of the Geological Department and Geophysical Section for their helpful suggestions. The Richmond Exploration Company generously agreed to the release of subsurface information from their wells north of Alturitas.

GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 706-715, 7 FIGS.

SEISMIC STUDIES ON ANTARCTIC ICE SHELVES*

EDWARD THIEL† AND NED A. OSTENSO‡

Three methods have been employed at Little America V to determine seismic velocity as a function of depth in the Ross ice shelf: (1) refraction-shooting interpreted by means of the Herglotz-Bateman-Wiechert integral, (2) seismic logging of a deep borehole, (3) Robin's formula relating P wave velocity to the density and temperature measurements made in the borehole. Results of the three methods are compared, discrepancies are discussed, and the preferred P and S velocity-depth profiles are obtained. From the profiles and the measurements of density in the borehole, a complete determination of the elastic properties of the ice shelf is possible.

Small velocity differences are obtained at depth by the methods of refraction-shooting and borehole-logging. The effects of crystal orientation on seismic velocity is discussed and found to be sufficient to account for the differences. A new determination of the variation of seismic velocity in ice as a function of temperature is made on the basis of recent experimental work.

INTRODUCTION

Dominating features of the Antarctic coast are the many ice shelves which combined represent 10 percent of the surface area of Antarctica (Figure 1). In many places the shelves are only a few kilometers wide, but in protected embayments are formed the vast plains of floating ice characteristic only of the southernmost continent. The largest of these, the Ross ice shelf, is approximately the size and shape of Texas with an average thickness of 450 m. Successively smaller are the Filchner, Larsen, and Amery ice shelves, though the latter is equivalent in area to the state of West Virginia. The total area of shelf-ice fringing Antarctica is 1,400,000 km².

A thorough study of the physical properties of ice shelves was undertaken during the International Geophysical Year. The seismic method was the most important technique employed. This paper includes the methods that have been used to obtain velocity control for the extensive program of seismic soundings and also points out to what extent seismology has contributed to our knowledge of the physical properties of ice shelves. In this regard, a deep borehole at Little America V provided a unique opportunity for studying the structure of ice at depth. The methods developed in Antarctica for the study of ice may suggest techniques for rocks of more complex lithology.

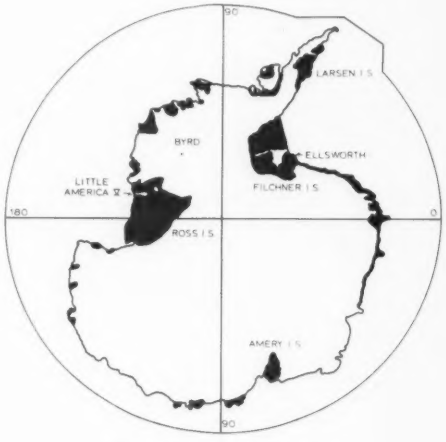

FIG. 1. Antarctic ice shelves.

DENSITY AND TEMPERATURE AS A FUNCTION OF DEPTH

The surface of an ice shelf consists of snow with a density of about 0.35 gm/cm³. Densification occurs under the effect of pressure until at a depth of approximately 50 m the permeability, though not the porosity, has vanished. The substance is then, by definition, ice.

A notable contribution to our knowledge of the variation of density and temperature as a function

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of depth within an ice shelf has resulted from the deep drilling program undertaken by the Snow, Ice, and Permafrost Research Establishment of U.S.A. Corps of Engineers (Patenaude, Marshall, and Gow, 1958; Ragle, Hansen, Gow, and Patenaude, 1959). Deep holes have been drilled and core recovered on the inland ice sheet at Byrd (80° S., 120° W.) and on the northeastern side of the Ross ice shelf at Little America V (78° 12′ S., 162° 16′ W.). In addition, core has been recovered by hand boring to 55 m depth at Ellsworth (77° 43′ S., 41° 08′ W.) on the Filchner ice shelf (Thiel and Behrendt, 1959a). The data on density and temperature as a function of depth are presented in Figures 2 and 3.

The density curves for ice shelf and ice sheet are similar except for three details. (1) The near surface density is greater on the ice sheet. This is believed to be related to differing meteorological conditions at the sites, including the effect of greater wind packing at Byrd. (2) There are anomalies in the Ellsworth and Little America V density curves at 45 and 55 m depth respectively. (3) The ice below a depth of 170 m is slightly more dense on the plateau than on the ice shelf.

The temperature curves are greatly dissimilar. The Little America V curve shows the effects of a warmer surface environment and of heating from below by a relatively warm ocean. Wexler (1959, 1960) has discussed the histories of the ice at Byrd and Little America V in terms of a theoretical interpretation of the temperature profiles.

The density and temperature data are basic to the velocity studies, as will be evident in the following sections.

VELOCITY AS A FUNCTION OF DEPTH

Oversnow traverse parties have visited extensive areas of the Ross and Filchner ice shelves. The seismic field program of these parties has consisted mainly of reflection shooting for determining ice thickness and ocean depth, refraction shooting for determining variations in the character of the near surface snows. Some data on velocity as a function of depth have resulted from these studies, although in most cases these data apply only to the upper part of the shelf. Because the velocity changes are greater near the surface, the shallow refraction studies are important in providing velocity control for the reflection work.

The discussion below is confined mainly to the work at Little America V where several different methods have been employed to study the variation of velocity with depth and where data from deep drilling are available.

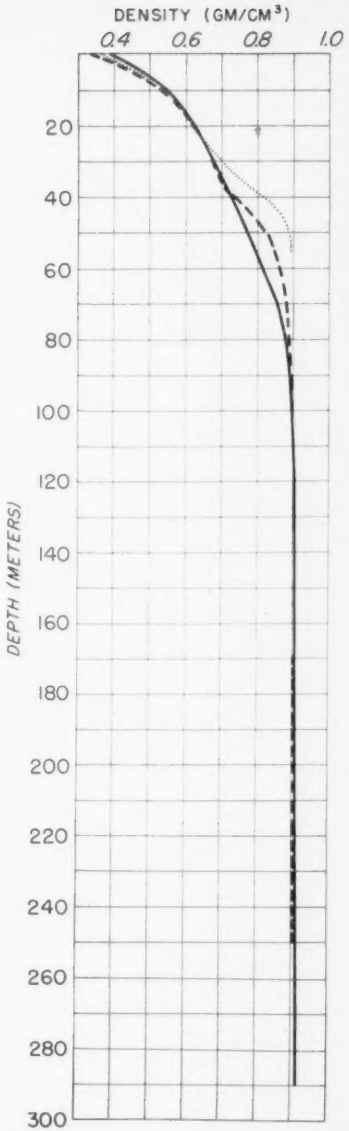

FIG. 2. Density as a function of depth at Byrd on the inland ice sheet (solid line), at Little America V on the Ross ice shelf (dashed line), and at Ellsworth on the Filchner ice shelf (dotted line).

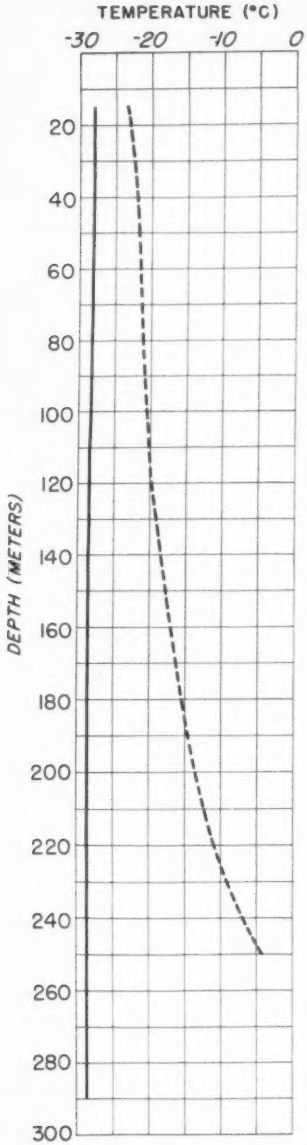

FIG. 3. Temperature as function of depth at Byrd on the inland ice sheet (solid line) and at Little America V on the Ross ice shelf (dashed line).

Refraction shooting

The theory of the interpretation of seismic travel-time curves for refracted waves in horizontal structures has been treated by Slichter (1932) as an extension of earlier work by Herglotz, Bateman, and Wiechert. Given a travel-time curve, the velocity as a function of depth may be computed by numerical integration from the relation,

$$z_{x_1} = \frac{1}{\pi} \int_{x=0}^{x=x_1} \cosh^{-1} \frac{V_{x_1}}{V_x} \, dx, \qquad (1)$$

where z_{x_1} is the depth corresponding to the velocity V_{x_1}. This is the maximum depth penetrated by the refracted wave first received at distance x_1. This formula is valid provided that the velocity does not decrease with depth anywhere between the surface and z_{x_1}.

The velocity variation as a function of depth had been determined by refraction shooting on the ice sheets of Greenland and Antarctica (Bentley, Pomeroy, and Dorman, 1957; Bentley, McGinnis, and Robinson, 1959). When the method was first applied on the Filchner ice shelf by Thiel and Behrendt (1959b), it was noted that the results did not agree with those obtained on the grounded ice sheets. In particular, the maximum observed P wave velocity was found to occur at a shallower depth on the ice shelf than on the grounded ice sheets (70 vs 350 m), and this maximum was less for the shelf than for the ice sheets (3,810 m/sec vs 3,865 m/sec). Similar results were found by Robinson (1958) on the Ross ice shelf and by Crary (1957) at Little America V. Figure 4 illustrates the discrepancy.

It was only after the refraction shooting had been completed that the density-depth data of Figure 2 became available as a result of drilling. A comparison of Figures 2 and 4 shows that, to a first approximation, the velocities determined by refraction shooting reflect the density of the ice at depth. The difference in velocity structure between grounded ice sheet and floating ice shelf is therefore, to a first approximation, the result of a difference in density structure. However, there is also a temperature effect. The heating of an ice shelf from below will lower the maximum observed velocity and cause it to occur nearer the surface. Finally, the effect of crystal orientation (see discussion below) is more pronounced at Little America V on the ice shelf than at Byrd on the grounded ice sheet. The three effects of density, temperature, and crystal orientation account

completely for the differences in velocity structure observed in Figure 4.

Seismic logging of deep borehole

During the 1958–59 Antarctic season a deep core drilling project was undertaken at Little America V as a part of a glaciological study of the physical properties of the Ross ice shelf. A seismic log of the borehole was run at the time the drilling project was nearing completion. Shortly after the seismic logging had been completed, salt water seepage partially refilled the hole and brought a halt to the drilling program. Core was recovered from a depth of 254 m, while the shelf thickness at this location was determined by reflection shooting to be 259 m.

An assembly consisting of a vertical geophone and a horizontal geophone was used to record both *P* and *S* waves. The assembly was lowered to the bottom of the hole. Upon an electrical signal from the surface, a spring system was released which coupled the assembly to the walls of the hole. With this system the geophones could be pulled upward any distance without sliding back down the hole and without putting a strain on the cable during the velocity measurement.

A number of methods of generating the seismic wave were tried; detonating caps at the surface, striking the steel casing near the top of the hole, striking steel plates on the snow surface, etc. By far the best results were obtained, particularly as regards the *S* wave, by hitting the drilling rig with a hammer. Travel-time measurements were made at two-meter intervals, and distance was measured by markings previously painted on the cable. A dynamometer bench test of the cable (Vector F 28 C 135 C) gave an elastic elongation of 0.05 cm for a 30-m length with a 20-kilogram tension, so that elongation of the cable under load is not significant. Figure 5 is a typical record.

The seismic velocity at any depth is obtained from the slope of the travel-time curve. Drawing the curve, even when the control points are numerous, and determining its slope are not clear-cut problems when one attempts to work to an accuracy of a few meters per second. In determining the slope, a partially transparent mirror was placed perpendicular to the curve and to the paper. When the two curves as seen in the mirror (one reflected and one transmitted) were coincident; the mirror was adjudged perpendicular to the curve, and a line was drawn along the base of the mirror. A perpendicular to this line gave the slope.

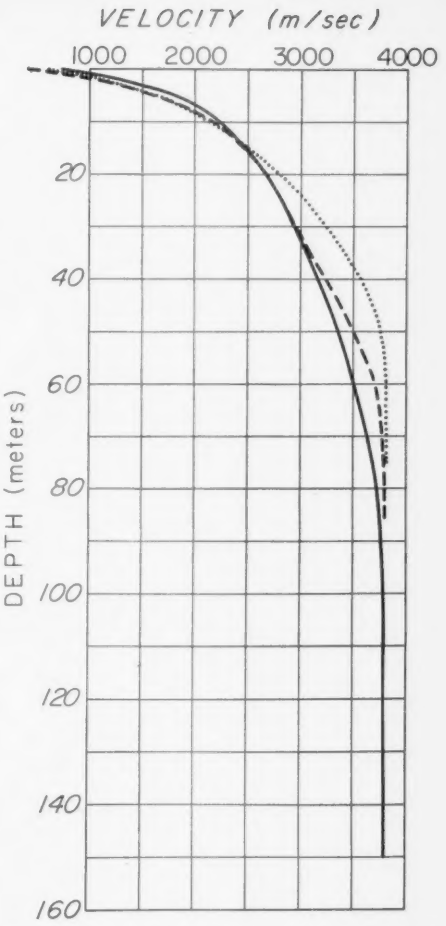

FIG. 4. Velocity-depth profiles at Byrd on the inland ice sheet (solid line), at Little America V on the Ross ice shelf (dashed line), and at Ellsworth on the Filchner ice shelf (dotted line).

The maximum velocities obtained by this method occur in the vicinity of 85–110 m depth. The values are:

$$\overline{V}_P = 3839 \text{ m/second, and}$$

$$\overline{V}_S = 1978 \text{ m/second.}$$

At greater depths the effect of temperature decreases the velocities.

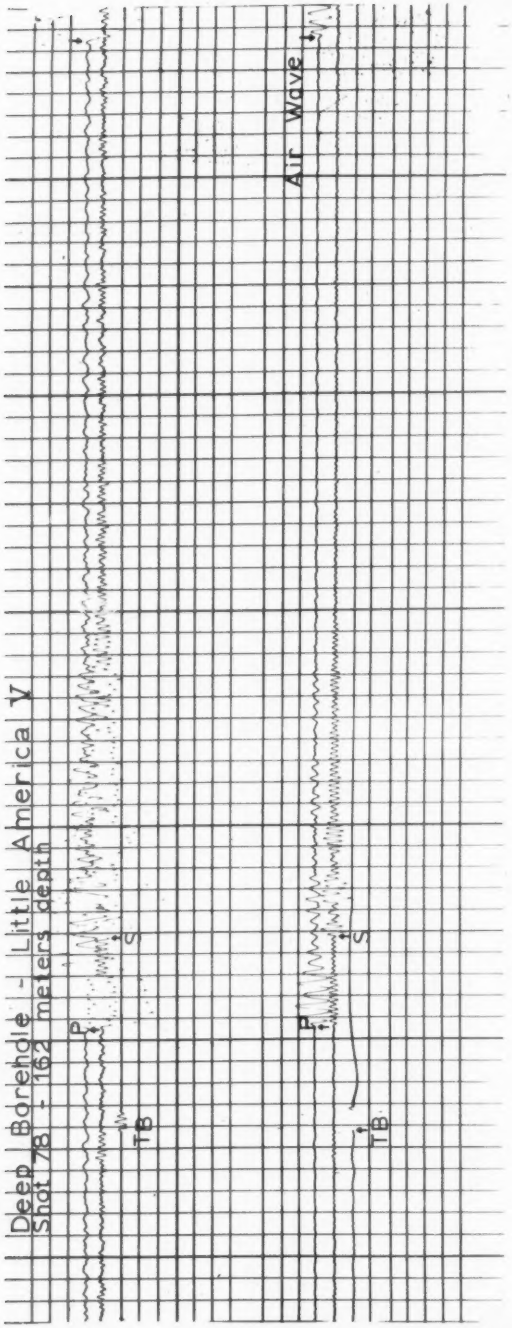

FIG. 5. Seismogram obtained during logging of the deep borehole at Little America V.

Laboratory studies of seismic velocity

Robin (1958) has used an ultrasonic pulse technique to determine the velocity of P waves in samples of firn and ice as a function of density and temperature.

The effect of temperature on velocity was determined for two types of samples, (1) a sample of density 0.89 made by freezing snow saturated with water and (2) a sample of snow compressed to approximately 200 atmospheres. The results are expressed by the formula,

$$V_{Pt} = V_{P_{-20}} - 2.3(t + 20), \qquad (2)$$

where V_{P_t} and $V_{P_{-20}}$ are the compressional velocities at $t°$ C and $-20°$C, respectively. The formula is valid for samples of density close to that of ice below $-10°$C.

The variation of velocity with density was determined using samples of ice and firn collected on the Jungfranjock. The relationship, using the less scattered points for specimens in which ice bands were not visible, is

$$\rho = 2.21 \times 10^{-4} V_P + .059. \qquad (3)$$

Specimens of density less than 0.4 apparently were not analyzed.

The combination relation is given by Robin as

$$\rho = 2.21 \times 10^{-4}(1 + 0.00061t)V_P + .059 \qquad (4)$$

when the temperature coefficient for firn is assumed to be the same as that for ice. The explicit expression for V_P is

$$V_P = \frac{\rho - .059}{0.000221(1 + 0.00061t)}. \qquad (5)$$

No similar studies have been reported for S waves. With the density and temperature data given in Figures 2 and 3, the velocity as a function of depth can be computed from the above formula.

Reflection shooting

A method of velocity computation proposed by Green (1938) gives the average velocity for a vertically traveling wave from the data contained on a reflection seismogram. For this method denote the horizontal distance between shotpoint and detector by D and the reflection time by t. Then a plot of D^2 vs t^2 gives a line, the slope of which is $1/\overline{V}^2$. In applying this method on an ice shelf, a correction is usually made for the upper 100 m, so the result obtained will apply to ice after the greater part of the densification process has occurred.

This method has been used on both grounded ice sheets and on floating ice shelves but not specifically in the Little America area. The difficulty is that where the shelf is relatively thin, as at the ice front, reflections from the ice-water interface are seldom observed. Therefore, there are no results by this method which are directly comparable with results obtained by the other methods.

COMPARISON OF METHODS

Near the snow surface

In comparing the results of velocity variation with depth by the different methods at Little America V, the greatest divergence is found at the surface. This is illustrated in Figure 6. Velocities determined by refraction shooting using the Herglotz-Bateman-Wiechert formula are low. The reason is that, when the wave length is large compared with the depth of penetration, a decrease in the velocity of the waves compared with that in an infinite medium must be expected. This has been pointed out by Robin (1958). The limiting velocity in this case with be that of longitudinal waves along a thin plate.

On the other hand, velocities determined by

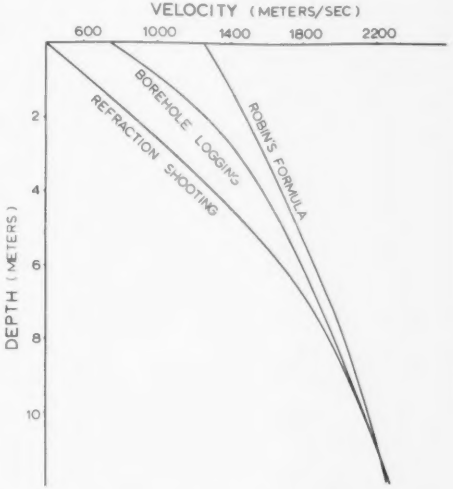

FIG. 6. Comparison of velocity-depth profiles obtained near the snow surface by three different methods. The results of borehole logging are adopted.

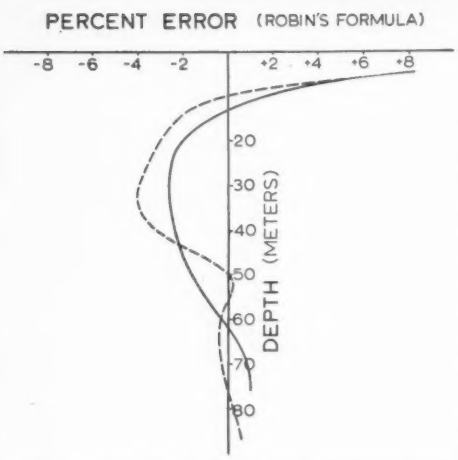

FIG. 7. Comparison of velocities computed from Robin's formula with velocities determined by refraction shooting at Byrd on the inland ice sheet (solid line) and at Little America V on the Ross ice shelf (dashed line).

Robin's formula from the density and temperature data are high. This is perhaps not surprising in that Robin's formula was not meant to hold for density values as low as those which exist at the snow surface.

Accordingly, the seismic logging of shallow boreholes is the preferred method of determining velocity near the snow surface.

Intermediate depths

The results obtained at intermediate depths (12 m–70 m) by refraction shooting and by Robin's formula are compared in Figure 7. Because the deep borehole at Little America V is cased with steel near the surface, results from seismic logging are not available above 44 m depth. It is evident that at intermediate depths the results computed from Robin's formula may be as much as three per cent low when compared with the field measurements.

Deep within the shelf

Between 70 m depth and the zone of maximum velocity, refraction shooting yields P wave velocities which are less than those obtained by borehole logging. Although the difference is small and might possibly be attributed to experimental error, it is worthwhile to search for a mechanism that might explain the observations. Crystal orientation would seem to be a logical candidate.

Petrofabric studies on ice specimens from glaciers indicate that there is a preferred crystal orientation in a flowing glacier (Rigsby, 1960). The basal plane of the hexagonal ice crystal tends to parallel the rock floor, so that the c axis is oriented vertically. This orientation is a result of flow and might be expected to develop at the head of an ice shelf when the ice moves rather rapidly downhill from the interior to reach shelf level. Alternatively, a preferred orientation may develop during the process of ice shelf spreading and thinning.

The ice cores from the deep boreholes that have been drilled at Little America V and Byrd have distinctly different petrofabrics. The ice beneath Little America V exhibits a preferred orientation which becomes stronger with depth (Ragle, Hansen, Gow, and Patenaude, 1959). No preferred orientation is evident in the Byrd core.

Accordingly, when a velocity characteristic of a certain depth in the ice shelf is sought, use of one particular experimental method could lead to error. Waves travel, for the most part, horizontally in refraction shooting. In borehole logging the waves travel vertically. In the former case somewhat smaller P wave velocities should be obtained than in the latter case, in agreement with our field observations.

In Table 1 the P wave velocities at depth are

Table I. Physical properties of the Ross ice shelf at Little America V as a function of depth

Depth (m)	Density (gm/cm³)	P Wave Velocity (m/sec)	S Wave Velocity (m/sec)	Poisson's ratio
0	.337	750	427	.261
2	.388	1,270	721	.262
4	.428	1,586	895	.266
6	.466	1,782	973	.288
8	.499	1,961	1,061	.293
10	.530	2,142	1,166	.290
12	.555	2,282	1,256	.282
14	.575	2,389	1,332	.274
16	.592	2,479	1,396	.268
18	.606	2,549	1,429	.271
20	.621	2,617	1,459	.274
30	.674	2,875	1,517	.287
40	.736	3,173	1,682	.304
50	.827	3,489	1,829	.310
100	.899	3,835	1,983	.318
150	.904	3,828	1,967	.320
200	.904	3,811	1,957	.321
240	.904	3,795	1,946	.322

the average of the values obtained by the different methods. It was not possible to obtain a similar average for the S waves because Robin's laboratory investigation did not involve a study of S waves. Therefore, the appropriate S wave values were determined indirectly. Poisson's ratio as a function of depth was computed from the P and S wave velocity data obtained by borehole logging. These ratios and the average P wave values were then used to compute the average S wave values. This use of average values means that the small effects of anistropy are ignored, momentarily.

Knowing the average P wave velocity, the average S wave velocity, and the density as a function of depth; it is possible to obtain the variation of all other elastic moduli with depth. The appropriate equations are as follows:

$$\sigma \text{ (Poisson's ratio)} = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)} \quad (6)$$

$$k \text{ (bulk modulus)} = \rho\left(V_P^2 - \frac{4}{3}V_S^2\right) \quad (7)$$

$$\mu \text{ (shear modulus)} = \rho V_S^2 \quad (8)$$

$$E \text{ (Young's modulus)} = \rho\left[\frac{3V_P^2 - 4V_S^2}{\left(\frac{V_P}{V_S}\right)^2 - 1}\right] \quad (9)$$

$$\lambda \text{ (Lame's constant)} = \rho(V_P^2 - 2V_S^2). \quad (10)$$

THE EFFECT OF CRYSTAL ORIENTATION

The petrofabric study of the Little America V core has not yet been completed by the SIPRE[1] group, so quantitative studies relating the degree of orientation to our seismic field measurements can not now be made. However, recent work in experimental crystallography has provided data on the elastic constants of single ice crystals from which the relationship between crystal orientation and seismic velocity may be deduced.

The elastic behavior of crystals is described by the following equations:

$$\sigma_i = \sum_{k=1}^{6} c_{ik}\epsilon_k; \quad \text{and} \quad \epsilon_i = \sum_{k=1}^{6} s_{ik}\sigma_k. \quad (11)$$

The c_{ik} are the elastic stiffness constants. The s_{ik} are the elastic compliance constants. They are connected through the relations,

$$\sum_{k=1}^{6} c_{ik}s_{jk} = \begin{cases} 1 \text{ for } i = j \\ 0 \text{ for } i \neq j. \end{cases} \quad (12)$$

Ice, which crystallizes in the hexagonal system, possesses five independent constants, c_{ik} or s_{ik}.

The values of the constants have been determined in a number of ways.

1. Penny (1948) undertook a theoretical treatment based on an old model of the ice crystal according to which the hydrogen atoms lie midway between the oxygens. Employing certain symmetry restrictions to this configuration and assuming that the tetrahedra of oxygen atoms which form the lattice are regular, the elastic stiffness constants were calculated using the experimental data available at the time for ordinary poly-crystalline ice.

2. Jona and Scherrer (1952) determined experimentally the elastic stiffness constants of single ice crystals from the optical diffraction patterns of crystals vibrating at high frequency at a temperature of -16°C. The experimental values of c_{ik} were somewhat lower than those deduced by Penny, but the relations among the c_{ik} which Penny had derived were found valid within the limits of experimental error.

3. Green and Mackinnon (1956) used an ultrasonic pulse technique to determine the elastic stiffness constants, c_{33} and c_{44}, of single ice crystals. The remaining three stiffness constants were obtained by substituting the values of c_{33} and c_{44} into Penny's relations among the constants.

4. Bass, Rossberg, and Ziegler (1957) determined the elastic compliance constants through measurements of the natural frequency of cylindrical rods and plates of crystalline ice in the temperature range -2°C to -30°C. The stiffness constants were calculated from the s_{ik} by means of formula (12).

The c_{ik} obtained by the various investigators are summarized in Table II. In all cases, except for c_{44}, the experimental values are less than Penny's theoretical values. A more recent model of the ice crystal proposed by Pauling (1935) postulates that the hydrogen atoms always lie closer to one oxygen neighbor than the other and that correlated jumping between potential

[1] Snow, Ice, and Permafrost Research Establishment.

Table II. The elastic stiffness constants of ice (c_{ik} in 10^{10} dynes/cm^2).

c_{ik}	Theoretical Penny, 1948	Experimental Jona & Scherrer, 1951	Experimental Green & Mackinnon, 1956	Experimental Bass, Rossberg, Ziegler, 1957	Experimental Average
c_{11}	15.2	13.845±0.08	13.33±1.98	13.3±0.8	13.49
c_{12}	8.0	7.07 ±0.12	6.03±0.72	6.3±0.8	6.47
c_{13}	7.0	5.81 ±0.16	5.08±0.72	4.6 ±0.9	5.16
c_{33}	16.2	14.99 ±0.08	14.28±0.54	14.2 ±0.7	14.49
c_{44}	3.2	3.19 ±0.03	3.26±0.08	3.06±0.015	3.17

minima is possible for many hydrogens at once. Thermodynamic measurements, observations of the dielectric constant, and neutron diffraction studies support the Pauling model over the simpler model employed by Penny. The fact that the experimental results disagree somewhat among themselves led Bass, Rossberg, and Ziegler to suggest a dispersion of the constants because the several investigators conducted their work in different frequency ranges.

Knowing the c_{ik} and the density, the velocities of P and S waves through the crystal in any specified direction are obtained by solving the Christofel equations (Love, 4th ed., 1927, page 298). In general, there will be three waves, one longitudinal and two shear, corresponding to a direction of propagation. For directions of travel parallel and perpendicular to the c axis, the relations are greatly simplified (Goens, 1937). For the hexagonal system we have, parallel to c axis,

$$V_P = \sqrt{\frac{c_{33}}{\rho}} \qquad V_{S_1} = V_{S_2} = \sqrt{\frac{c_{44}}{\rho}}, \tag{13}$$

and perpendicular to c axis,

$$V_P = \sqrt{\frac{c_{11}}{\rho}} \qquad V_{S_1} = \sqrt{\frac{c_{44}}{\rho}}$$

$$V_{S_2} = \sqrt{\frac{c_{11} - c_{12}}{2\rho}}.$$

Using the average experimental values listed in Table 2 and a density of .917 for ice[2] (Seligman, 1950), the results are,
parallel to c axis

$$V_P = 3975 \text{ m/sec}$$

$$V_{S_1} = V_{S_2} = 1859 \text{ m/sec}, \quad \text{and}$$

perpendicular to c axis,

$$V_P = 3835 \text{ m/sec} \qquad V_{S_1} = 1859 \text{ m/sec}$$

$$V_{S_2} = 1956 \text{ m/sec}.$$

The difference in the velocity of the P wave that might be expected to result from complete crystal orientation is, according to the above analysis, about four percent. The effect of crystal orientation is therefore sufficient to account for the difference in velocity which we have observed by refraction shooting and borehole logging at Little America V.

VARIATION OF VELOCITY WITH TEMPERATURE

Because the temperature coefficient of velocity is of considerable importance in glacio-seismological research, it is of interest to point out how the experimental work of Bass, Rossberg, and Ziegler may be used for a determination of this coefficient. The measured values of the s_{ik} at −5°C and −25°C are converted to values of c_{ik} by means of equation (12). The corresponding values for V_P and V_S are computed from equations (13). The temperature coefficient for V_P is then

$$\frac{V_{P-25^\circ\text{C}} - V_{P-5^\circ\text{C}}}{20}$$

with similar equations for V_S. This gives,

for V_P, −3.8 m/sec/°C, and

for V_S, −1.4 m/sec/°C.

Unfortunately the conversion by means of equation (12) may lead to considerable inaccuracy, and the c_{ik} determined by other investigators are not known as a function of temperature.

A determination of the temperature coefficient may also be made from the field study. Below 135 m depth in the Little America V borehole, the density and Poisson's ratio are nearly constant. If

[2] This is the theoretical density of pure ice derived from the lattice constant of ice formed from distilled water at 0°C.

the velocity decrease below this depth is attributed solely to the effect of temperature, the temperature and seismic velocity logs yield,

for V_P, -7.4 m/sec/°C; and

for V_S, -3.4 m/sec/°C.

Both of these determinations exceed the value obtained by Robin in the laboratory. From equation (2) we have,

for V_P, -2.3 m/sec/°C; and

for V_S, not determined.

The values, however, are much less than the coefficient of -18 m/sec/°C for P waves reported by Joset and Holtzscherrer (1954) from seismic field studies in Greenland.

ACKNOWLEDGMENTS

Mr. R. Ragle was in charge of the SIPRE core drilling program at Little America V, and we wish to acknowledge his cooperation in permitting us to run the seismic log of the borehole during a late stage of the drilling program. Mr. J. A. Bender of SIPRE kindly supplied the borehole density and temperature data in advance of publication by his organization. The information cited on crystal orientation in the deep boreholes was obtained during conversations with Mr. A. Gow and is quoted with his permission. In Figure 4, the velocity curves for Little America V and Byrd are taken from unpublished papers by Drs. A. P. Crary and C. R. Bentley. Our studies at Little America V were a part of the 1958–59 airlifted geophysical program supported by grants to the University of Wisconsin from the National Science Foundation as a part of the U. S. Antarctic Research Program.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 716–726, 3 FIGS.

AN AEROMAGNETIC PROFILE FROM ANCHORAGE TO NOME, ALASKA*

ELIZABETH R. KING†

A total-intensity profile was obtained on a 500-mile flight by a U. S. Geological Survey airplane from Anchorage to Nome, Alaska, on May 4, 1954. The average flight altitude was 6,000 ft above sea level except over the Alaska Range where the flight altitude was 9,000 ft. This profile crossed eight of the major tectonic elements of Alaska at right angles to their trend and gives valuable regional information in an area where other geophysical and geological information is scarce or lacking.

The profile has a net gradient downward to the northwest, most of which is ascribed to the component of the earth's main magnetic field along the flight traverse. The great variety of magnetic anomalies which are superimposed on this gradient originate from variations in lithology along the traverse. All the magnetic anomalies, except a large one over the Yukon River, are caused by magnetic rocks at or near the surface.

The magnetic profile may be divided into four major segments and nine subsegments, each having a characteristic magnetic pattern. Most of these can be related to a tectonic unit. The large plutons of the Talkeetna geanticline are clearly defined by a group of anomalies having the highest amplitudes of any on the profile. The Matanuska geosyncline to the east is represented by a 25-mile section of sloping profile consistent with a thick sedimentary section but indicating that the geosyncline is comparatively narrow near Anchorage. The 200-mile central magnetic segment is relatively free from all but very minor anomalies. This segment includes the Alaska Range geosyncline, the Tanana geanticline, and the Kuskokwim geosyncline; showing only slight magnetic contrasts between each of these elements. The two geosynclines either have thick Mesozoic sedimentary sections or have underlying crystalline rocks which are low in magnetic susceptibility at shallow depths. The rocks of the geanticline have a low but not negligible magnetic susceptibility and are predominantly Paleozoic sedimentary rocks. A single 300-gamma anomaly on the west edge of the central segment is caused by a small, mafic intrusive body in the Paleozoic metamorphic rocks of Mt. Hurst. West of this anomaly the profile consists of a series of small sharp anomalies which are probably caused by Paleozoic metavolcanic rocks of the Ruby geanticline. The second largest anomaly on the profile is in the Koyukuk geosyncline over the Yukon River. The source is calculated to be more than a mile deep and may be an intrusive body at least 15 miles wide. This anomaly is flanked by 20-mile sections of flat or sloping profile which indicate areas of thick sedimentary rocks, particularly in the region west of the Yukon River. The 150-mile Norton Sound magnetic segment on the western end of the profile consists of many closely spaced anomalies produced by rocks which are either volcanic or similar to the Seward complex.

Of the four Cenozoic basins or lowlands crossed by the profile, three are underlain by rocks of moderate to high magnetic susceptibility at shallow depths. These are the Cook Inlet basin, part of which overlaps rocks of the Talkeetna geanticline, the Innoko basin of central Alaska which overlies the rocks of the Ruby geanticline, and the Norton basin, in which sedimentary deposits are thin or absent. The fourth, the Minchumina basin, is underlain by the low-susceptibility rocks at the Tanana geanticline, which are also probably close to the surface.

INTRODUCTION

The recent intensified interest in the geology of Alaska, particularly its potential petroleum provinces, coupled with the scarcity of information for much of the State, lends considerable importance to a 500-mile aeromagnetic profile that extends across all the major tectonic elements of southwestern Alaska (Figure 1). This profile was recorded by the U. S. Geological Survey along a traverse from Anchorage to Nome, Alaska, on May 4, 1954, as part of a broader investigation of areas favorable for oil. East of the Alaska Range the profile crosses the area covered by an aeromagnetic survey of Cook Inlet (Grantz et al, 1960). The profile does not cross any other aeromagnetic surveys of the U. S. Geological Survey. West of the lower Yukon River it is less than 70 miles south of the Koyukuk Basin profiles (Zietz et al, 1959), and it is approximately 100 miles southwest of a group of lines across the northern end of the Minchumina basin (Andreasen, 1960). This profile is the only aeromagnetic data available at the present time for a rough and inaccessible region of more than 100,000 square miles from the western slopes of the Alaska Range to the eastern shore of Norton Sound; from Lake Minchumina and the Yukon River on the north to Illiama Lake, Bethel, and Cape Dall on the south. The western end of the

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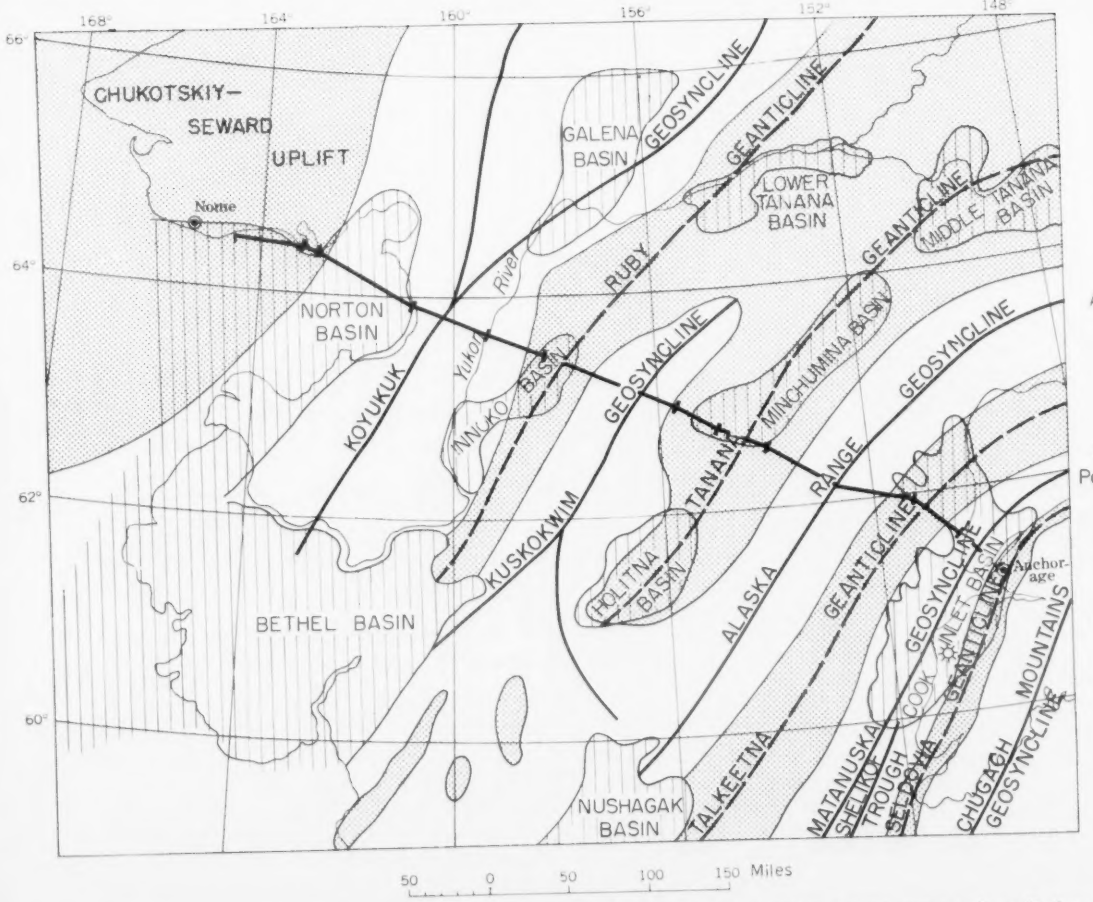

FIG. 1. Tectonic map of southwestern Alaska (after Payne, 1955) showing the location of the aeromagnetic profile from Anchorage to Nome.

profile crosses the shallow waters of Norton Sound, for which geologic information is lacking.

This profile provides a sample of the magnetic expression characteristic of the geologic section traversed. In particular, it indicates the location and probable extent of magnetic rocks such as volcanic and plutonic bodies. Even more significant to petroleum geology are the parts of the profile across the several major sedimentary basins for which the magnetic data do not indicate near-surface igneous rock. From an analysis of the magnetic anomalies, approximate thicknesses of sedimentary overburden may be obtained, within the limitations inherent in using a single profile. In view of the pronounced linearity of the prevailing tectonic trends in Alaska, this profile suggests the type of magnetic pattern associated with each of the eight tectonic units crossed.

FIELD WORK

The traverse was flown with the U. S. Geological Survey's DC-3-type aircraft, equipped with an AN-ASQ-3A fluxgate magnetometer which made a continuous record of changes in the intensity of the earth's total magnetic field (Balsley, 1952). The traverse was along established airways, and good weather permitted accurate visual location by the observer en route. The twelve control points, averaging 50 miles apart, are nearly all readily identifiable landmarks which were plotted to available topographic base maps with an accuracy of about one mile. There is a 5-mile circle of uncertainty for the change in course over the Alaska Range, which occurred midway between two control points, and for the terminal point on the northwest end, which was over water. The control points are shown as bars on Figure 1 and as tick marks accompanied by a brief description on the magnetic profile (Figures 2, 3). The traverse was flown at approximately 6,000 ft above sea level except over the Alaska Range where it was necessary to climb to 9,000 ft. The height of the aircraft above sea level is shown on Figures 2 and 3, accurate to 200 ft or better.

The topographic profile of the ground shown on Figures 2 and 3 has a vertical exaggeration of ten and is based on data from 1:250,000 scale reconnaissance topographic maps of the U. S. Geological Survey (Anchorage, Tyonek, Talkeetna, McGrath, Medfra, Ophir, Unalakleet, and Norton Bay). Elevations are known only approximately, if at all, in some of the more mountainous regions. Inexact location of the flight traverse introduces further uncertainties; but, from a regional point of view, this profile adequately represents the terrain below the aircraft. The height of the aircraft above ground ranges from about 6,000 ft over the low-lying regions at either end of the profile to 2,000 ft over the Alaska Range.

GEOLOGIC RÉSUMÉ

Some understanding of the geologic history of Alaska is necessary to make a meaningful interpretation of the aeromagnetic profile. The résumé that follows is derived largely from a report by Miller, Payne, and Gryc (1959) on the possible petroleum basins of Alaska.

Alaska is in the broad mountainous belt of western North America that forms part of the circum-Pacific tectonic system. This belt is made up of a group of large, parallel, tectonic elements which can be traced more or less continuously southward through Canada. Thus, the Brooks Range in Northern Alaska corresponds to the Rocky Mountains, the Alaska Range and Talkeetnas are the Alaskan counterparts of the Sierra-Cascades, and the Chugach-Kenai Mountains southeast of Cook Inlet are analogous to the Coast Ranges west of the Great Valley of California.

The oldest known rocks in Alaska are Precambrian metamorphic rocks, some of which, such as the Birch Creek schist in central Alaska, are metasedimentary rocks. During the Paleozoic, Alaska was a region of subsidence and sedimentation. South of the Yukon River the Paleozoic section contains abundant volcanic material characteristic of the volcanic archipelago assemblage of the western Cordillera of North America (Eardley, 1951, p. 516). At least two major orogenies during the Paleozoic involved considerable deformation but little or no intrusive activity.

The present tectonic pattern of alternating geanticlines and geosynclines, as shown in Figure 1, is, for the most part, the result of successive periods of deformation and deposition during and since the Mesozoic along the same or similar arcuate trends. Major orogenies involving folding, faulting, and uplift accompanied by extensive igneous intrusions and associated mineralization took place in the Jurassic and Cretaceous, and during the Late Cretaceous to early Tertiary in a period of deformation corresponding to the

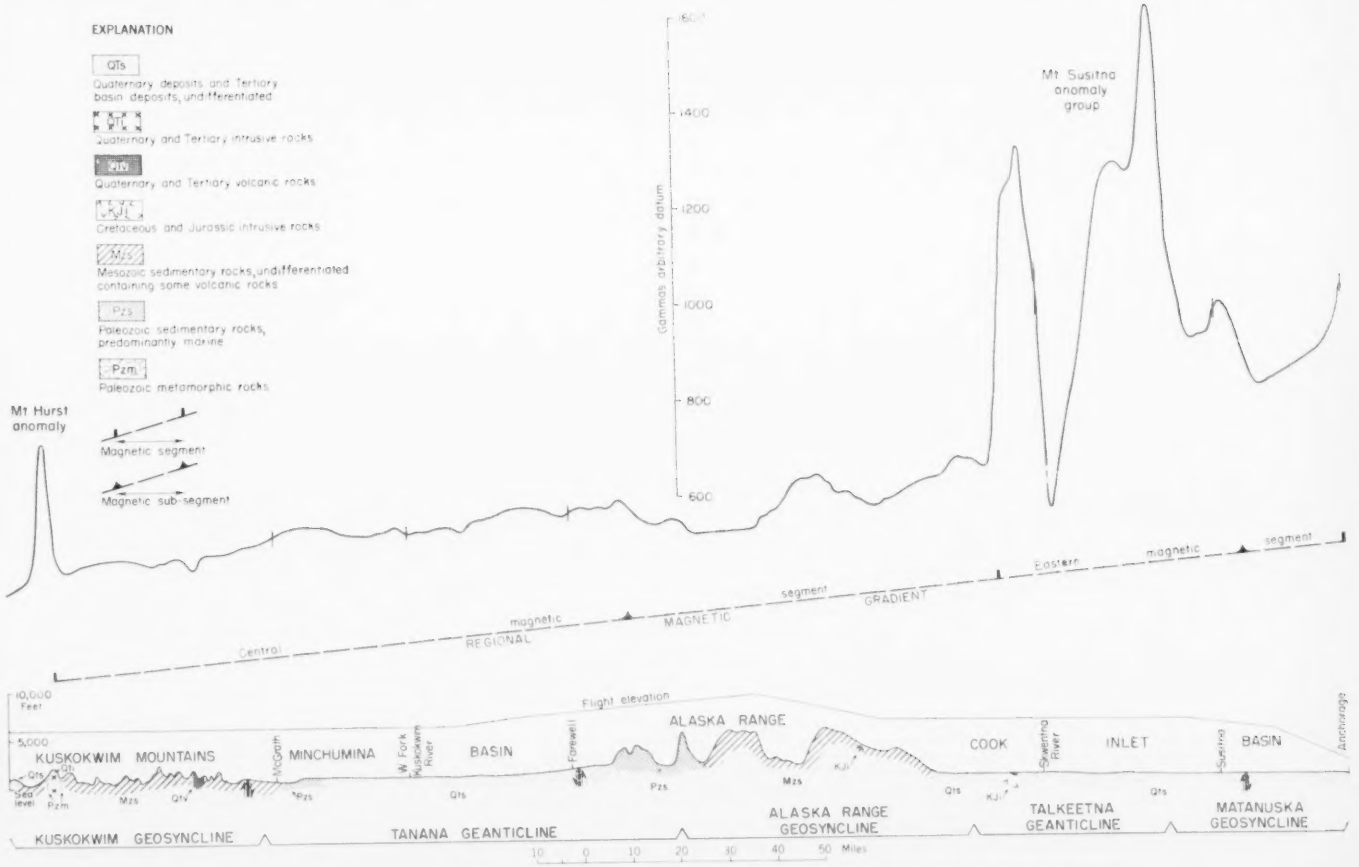

FIG. 2. Southeastern half of the aeromagnetic profile from Anchorage to Nome, Alaska, showing generalized lithology and approximate boundaries of the major tectonic units.

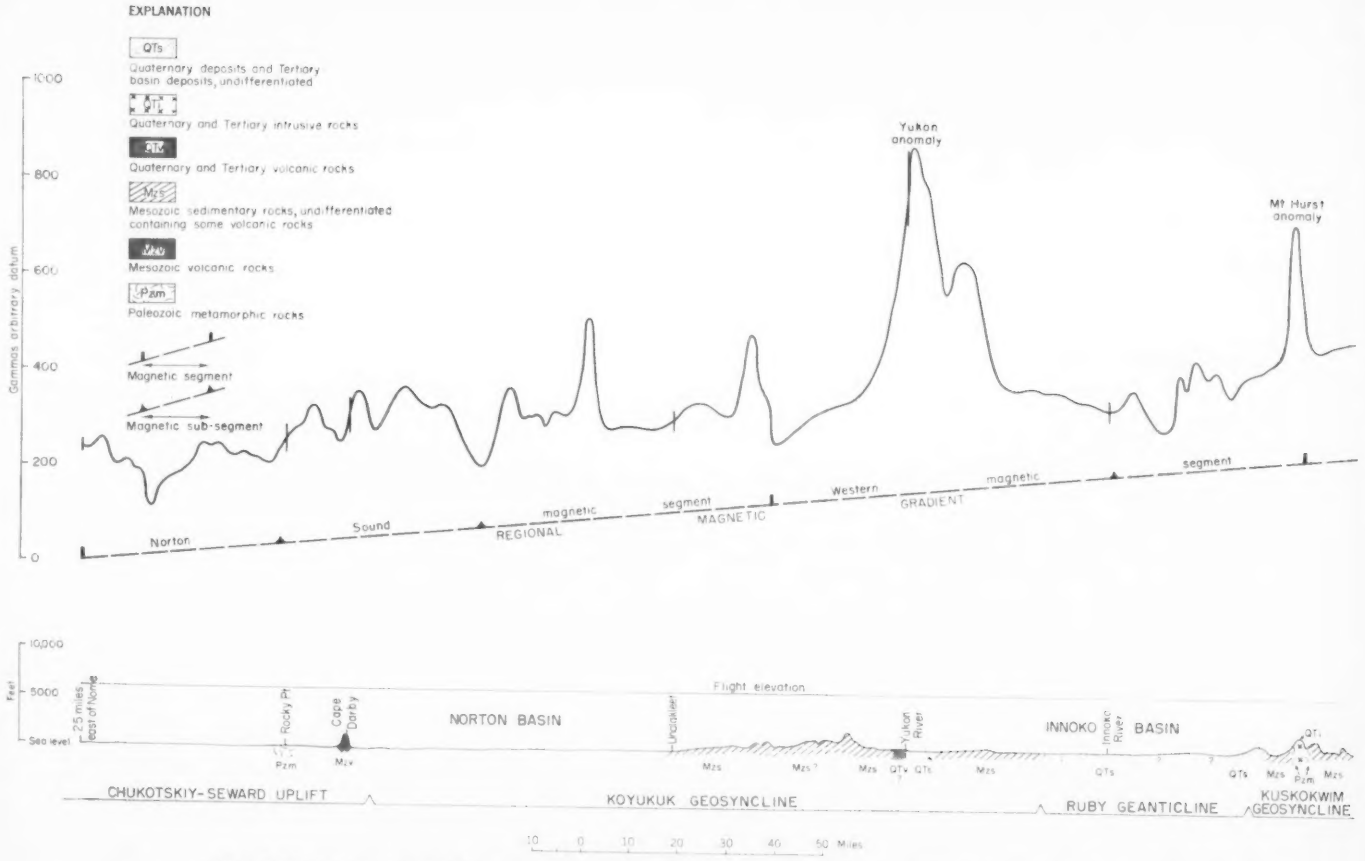

FIG. 3. Northwestern half of the aeromagnetic profile from Ancohragė to Nome, Alaska, showing generalized lithology and approximate boundaries of the major tectonic units.

Laramide. An orogeny in late Tertiary to early Quaternary time interrupted marine sedimentation and produced local lowlands or basins of deposition. Volcanism in southern and western Alaska and faulting, as shown by sharp escarpments and seismic acitivy off the coast, are evidence of continuing activity at the present time.

The tectonic map (Payne, 1955) (Figure 1) shows that the Mesozoic sedimentary rocks are largely confined to the geosynclinal belts in contrast to the Precambrian and Paleozoic rocks which tend to occur in cores of the anticlinoria. The units on the map are highly generalized. The areas shown as Precambrian and Paleozoic include large amounts of younger sedimentary and igneous material. Those shown as Mesozoic include some Paleozoic rocks as well as a considerable amount of Cenozoic material which is shown separately only in the localized basins of deposition. Many of the Mesozoic geosynclinal belts of deposition were subsequently elevated into the present mountain ranges, namely the Alaska Range, Kuskokwim Mountains, and the unnamed group of hills between the Yukon River and Norton Sound, whereas the geanticlines of older rocks have become low-lying areas in which the Cenozoic lowlands or basins have developed (see the topographic profiles on Figures 2, 3). These basins, according to Payne (1955), are the Cook Inlet basin, Minchumina basin, Innoko basin, and the Norton basin, into which the Yukon is building a delta at the present time. The surficial deposits in the basins are predominantly Quaternary. Tertiary rocks are found in or marginal to some of the basins, suggesting the presence of a Tertiary section of some thickness beneath the Quaternary, in which case the basins may be structural in origin (Miller et al, 1959).

The various rock units which appear on the geologic map of Alaska (Dutro and Payne, 1957) along this traverse have been grouped into seven categories which are shown on Figures 2 and 3. Because sedimentary rocks have negligible magnetic susceptibility, sedimentary units within the Paleozoic, Mesozoic, and Cenozoic are not differentiated. However, some underlying Precambrian metamorphic rocks have been included with the Paleozoic sedimentary rocks, which are themselves metamorphosed to different degrees. The Mesozoic and Cenozoic units contain igneous material, both extrusive and intrusive, which has not been shown separately on the geologic map (Dutro and Payne, 1957). As far as possible, the rocks which may have an appreciable magnetic susceptibility (Cenozoic volcanic rocks, Cenozoic intrusive rocks, Mesozoic volcanic rocks, Mesozoic intrusive rocks, and Paleozoic metamorphic rocks) are shown as separate units (Figures 2, 3).

It was not possible to show the structure of the rocks along the flight path, other than to indicate a few of the larger faults, because little detailed structural information is available. The Paleozoic and Mesozoic rocks are folded and faulted, with dominant northeast trend parallel to the overall tectonic pattern.

The major tectonic elements which are crossed by the aeromagnetic profile are the Matanuska geosyncline, the Talkeetna geanticline, the Alaska Range geosyncline, the Tanana geanticline, the Kuskokwim geosyncline, the Ruby geanticline, the Koyukuk geosyncline, and the Chukotskiy-Seward uplift (Figure 1). The approximate horizontal extent of each of these elements is shown beneath the geologic profile on Figures 2 and 3.

The Matanuska geosyncline, in the region crossed by the profile, contains a thick sequence of Mesozoic marine sedimentary rocks which are covered by Tertiary and Quaternary deposits of the Shelikof trough and Cook Inlet basin. Fifty miles south of the profile on the Kenai peninsula exploratory drilling in Mesozoic and Cenozoic rocks reached 15,000 ft and yielded oil in commercial quantities. The Talkeetna geanticline, part of which is covered by deposits of the Shelikof trough and Cook Inlet basin, consists of extensive Jurassic and Cretaceous diorite and granite plutons intruded into Early Jurassic and older host rocks. The eastern boundary of the Talkeetna geanticline appears to be a fault contact in many places. The Alaska Range geosyncline is composed of Mesozoic sedimentary rocks which have been intensely deformed and in many places intruded by granitic material. Most of the Tanana geanticline crossed by the traverse is covered by Cenozoic deposits of the Minchumina basin, but Precambrian and Paleozoic sedimentary rocks are at the surface along both the southwest and northeast margins. They probably underlie the entire basin. The Kuskokwim geosyncline is a broad belt of Cretaceous sedimentary rocks which contain many small Tertiary intrusives as well as some volcanic material. On the northwest a small area in the vicinity of Mt. Hurst consists of Paleozoic metamorphic rocks that probably are part of

the older metamorphic complex which characterizes the adjacent Ruby geanticline (Figure 3). The Ruby geanticline consists of Precambrian and early Paleozoic schists and later Paleozoic rocks, largely volcanic, with associated greenstones and siliceous rocks which form part of the volcanic archipelago assemblage deposited during the latter part of the Paleozoic (Eardley, 1951). Cretaceous sedimentary rocks predominate in the Koyukuk geosyncline. Large areas are unmapped, particularly in the region south of the profile; but the north-south trends of the topography indicate a linear structural pattern in these rocks. Volcanic rocks are exposed in several places along the west bank of the Yukon River as well as along much of the southern shore of Norton Sound, and small intrusive masses are present in the geosyncline. The Chukotskiy-Seward uplift, of which the mountainous Seward Peninsula is a part, is a structurally complex region of Precambrian and Paleozoic metamorphic rocks which are host to much intrusive and extrusive material of various ages. The Norton basin, coextensive with Norton Sound and the delta of the Yukon River, contains Cenozoic sedimentary rocks that cover the western part of the Koyukuk geosyncline and all of the Chukotskiy-Seward uplift crossed by the profile.

THE MAGNETIC PROFILE

General Characteristics

The aeromagnetic profile (Figures 2, 3) has an arbitrary magnetic datum. Small, short period irregularities of 5 gammas or less which are a combination of equipment noise, slight irregularities introduced in the compilation process, and very minor geologic effects, have been eliminated by smoothing. The profile is 600 gammas higher at Anchorage than at Nome. This is a gradient downward to the northwest of slightly more than one gamma per mile and is shown on Figures 2 and 3 as a dashed line. This gradient is the combined effect of instrumental drift, the diurnal variation, and the component of the earth's main magnetic field along the flight path. The instrumental drift was minimized by a one-hour warmup of the equipment prior to takeoff. Although the diurnal variation in Alaska is generally greater than in latitudes farther south and magnetic storms are common, a check of the magnetograms for the U. S. Coast and Geodetic Survey stations at Sitka, College, and Barrow showed no unusual magnetic activity during the flight period. Both types of drift were also minimized by the short flying time of $3\frac{1}{4}$ hours and probably account for only a small part of the 600 gammas observed. The U. S. Coast and Geodetic Survey's Total Intensity Magnetic Chart for 1955 shows a 4- to 5-gamma per mile gradient in a direction at right angles to the flight path. For a gradient of this magnitude, a shift in direction of less than 15 degrees to the west will give the gradient observed.

Vestine's tabulated values of the total magnetic field (Vestine et al, 1947), although they are for 1945, show a difference of about 600 gammas between Nome and Anchorage, which is in agreement with the observed profile. The gradient steepens the northwest sides of individual anomalies on the profile but not enough to affect their interpretation materially.

The aeromagnetic profile has been divided into four major segments which are labeled on the regional gradient line on Figures 2 and 3. The eastern segment is 75 miles long and includes the group of anomalies near Anchorage which have been called the Mt. Susitna anomaly group by Grantz et al (1960). These anomalies have the highest amplitudes of any on the profile, nearly 1,000 gammas in all. A nearly flat central segment of 200 miles, with only irregular, low-amplitude anomalies, lies between the Mt. Susitna anomaly group and the narrow, 300-gamma Mt. Hurst anomaly. Between the Mt. Hurst anomaly and the first sharp anomaly west of the 500-gamma Yukon anomaly is a more heterogeneous western segment of more than 100 miles. The remaining 150 miles, which is almost entirely over Norton Sound, consists of numerous 50- to 150-gamma anomalies, many of which are complex; that is, composites of closely spaced anomalies.

In each of these major segments two or more distinct subdivisions may be recognized. These subsegments are set off by tick marks on the regional gradient line. The eastern segment consists of two parts, the Mt. Susitna anomaly group, including the small anomaly on the southeast flank, and the short sloping part of the profile nearest Anchorage. The central segment, although of low magnetic relief, has a more variable character in the eastern third than in the higher and more uniform subsegment to the west. The western segment has an eastern subsegment of numerous small, sharp anomalies and a western subsegment that is fairly flat except for the Yukon

anomaly. The highly anomalous Norton Sound segment has three subsegments; the part east of the prominent 150-gamma low near the middle of the segment, the group of anomalies between this low and Rocky Point, and a lower section at the west end of the profile.

Interpretation Methods

The magnetic anomalies on the profiles are produced by variations in lithology in the upper part of the crust, principally by variations in the amount of magnetite in the rocks. The largest anomalies are usually produced by igneous rocks, especially the more mafic types such as diabase and gabbro, although some of the metamorphic rocks also can have a fairly high magnetic susceptibility. For the purposes of this study, the sedimentary rocks may be considered nonmagnetic, in line with results of magnetic surveys in a number of sedimentary areas. Consequently, large accumulations of sedimentary rocks in a geosyncline will give a smoother magnetic profile than the Precambrian and Paleozoic rocks of the geanticlines which have been metamorphosed and intruded by igneous rocks. Not enough is known of the exact lithology and subsurface structure to make detailed correlations feasible except in a few places. Therefore, emphasis is placed on the contrasts between the tectonic belts, particularly the horizontal extent and thickness of sedimentary rocks in the geosynclines.

Depth estimates were made on several of the individual anomalies on the profile using methods described by Vacquier et al (1951). These methods are based on the assumption that an anomaly is caused by a large mass of rock of uniform magnetic susceptibility that has a flat top and vertical sides which extend downward for a great distance. An estimate of the depth of burial of such a mass can be obtained by measuring the horizontal extent of the steepest gradient on the flank of the anomaly, or, where the anomaly is small and sharp, by measuring its width at half the maximum amplitude. The reliability of such determinations depends on the validity of the initial assumption; the absence of disturbing effects from other magnetic bodies; and in this case of a single profile, the trend of the anomaly, which must be at right angles to the profile. Although the magnetic trends are probably transverse to the flight line and the initial assumption is reasonably approximated, few anomalies on the profile are free of disturbing effects from other magnetic bodies and depth estimates are used primarily to establish whether near-surface magnetic rocks are present.

Relation of the Magnetic Profile to Tectonic Elements

Eastern Magnetic Segment. The eastern magnetic segment coincides roughly with the Matanuska geosyncline and Talkeetna geanticline as shown on Payne's generalized tectonic map (1955). The only part of this segment underlain by a thick section of nonmagnetic rocks has been set off as a 20-mile wide subsegment on the southeast end of the profile, between Anchorage and the buried fault near Susitna. This portion of the profile represents the much restricted width of the Matanuska geosyncline near Anchorage. The remainder of the eastern magnetic segment consists of the Mt. Susitna anomaly group. These large-amplitude anomalies are produced by highly magnetic plutonic rocks of Jurassic and Cretaceous age in the Talkeetna geanticline. Although these rocks crop out along the flight path in only a small area on the western side of the Talkeetna geanticline, they are exposed at the surface over large areas on either side of the flight path. A depth estimate made on the west flank of this anomaly group indicates that magnetic rocks are not more than 1,000 ft below the surface. Although none of the other anomalies are amenable to analysis, their very steep gradients are indicative of shallow sources. On the basis of the magnetic data, it is inferred that these rocks are present under a thin cover of Tertiary and Quaternary sedimentary deposits eastward as far as the buried fault near Susitna. The remarkable persistence of linear magnetic trends in these tectonic provinces is very well displayed by the aeromagnetic survey of Cook Inlet which extends for 150 miles to the south and 50 miles to the north (Grantz et al, 1960).

Central Magnetic Segment. The central segment includes three tectonic units, the Alaska Range geosyncline, the Tanana geanticline, and the Kuskokwim geosyncline. The small magnetic relief of this part of the profile indicates the presence of rocks with small susceptiblities such as metamorphosed sedimentary rocks and sedimentary rocks that contain only minor amounts of volcanic or intrusive rocks.

The more variable eastern subsegment coincides with the Alaska Range geosyncline in which

the rocks are predominantly sedimentary, and also includes a strip of older rocks concealed by alluvial deposits on the eastern slope of the Alaska Range where the Talkeetna geanticline is locally wider than indicated by Payne's map (1955). The numerous small irregularities on the magnetic profile may be caused by small patches of intrusive rocks or Lower Jurassic volcanic rocks, and by Precambrian rocks that form the Talkeetna geanticline. Topography may also play a part in producing a more irregular pattern in this section of the profile, as the ground-to-plane distance was least here and varied by 3,000 to 4,000 ft over relatively short distances. However, the western ridge of Mesozoic rocks has no magnetic expression and is apparently entirely sedimentary.

The magnetic profile is consistently higher over the Tanana geanticline than over the Alaska Range geosyncline and has numerous small anomalies of 10 gammas or less. There is no significant change in the character of the profile over the Minchumina Lowland in the central part of the Tanana geanticline where Quaternary alluvial deposits cover the older rocks. It is therefore concluded that these deposits are not thick and that the rocks underlying them do not differ greatly from the Paleozoic rocks exposed at the margins of the geanticline. Because of the slightly higher level of the profile, the Paleozoic rocks of the Tanana geanticline appear to have little but not negligible susceptibility, and the small anomalies arise from local susceptibility contrasts caused by metamorphism or small amounts of igneous material. There is no indication of large igneous plutons with high magnetic susceptibility in the Tanana geanticline either along this profile or 100 miles to the north on a group of short aeromagnetic profiles across the northern end of the Minchumina Lowland (Andreasen, 1960).

The part of the central magnetic segment associated with the Kuskokwim geosyncline is very similar to that associated with the Tanana geanticline and cannot be clearly distinguished from it. It tends to be slightly lower and smoother than the section to the east; but it has several small but quite distinct anomalies, one of which is a negative anomaly associated with a small area of Cenozoic volcanic rocks. Many small areas of Tertiary intrusive rocks have been mapped both to the north and south in the Kuskokwim geosyncline, and the flatness of the profile across this geosyncline may be somewhat fortuitous. It is concluded that the rocks of the geosyncline are predominantly nonmagnetic Mesozoic sedimentary rocks underlain by a basement of Paleozoic or older rocks which are either deep or have little magnetic expression. These basement rocks may be similar to those which crop out to the east in the Tanana geanticline. It is also concluded that the many small Tertiary intrusives on either side of the profile are isolated units and not part of a continuous subsurface intrusive mass which would be evident in the magnetic pattern.

The boundary between the Mesozoic rocks of the Kuskokwim geosyncline and the Precambrian and Paleozoic metamorphic rocks of the Ruby geanticline is marked by a series of salients of the latter rocks into the geosynclinal area. One of these forms the ridge containing Mt. Hurst. The source of the Mt. Hurst magnetic anomaly is calculated to be at the surface and proves to be a body of pyroxenite shown on the detailed geologic map of the area (Mertie and Harrington, 1924, p. 68). The flat magnetic pattern of the central segment is repeated for a short distance west of this anomaly over the Mesozoic sedimentary rocks along the western margin of the Kuskokwim geosyncline.

Western Magnetic Segment. The western magnetic segment is composed of several distinct magnetic patterns which reflect the complex geology of the region comprising the Ruby geanticline and the Koyukuk geosyncline. The part of the profile east of the Innoko River, except for the small flat section near Mt. Hurst which is related to the Kuskokwim geosyncline, consists of a series of small sharp anomalies which may be produced by metamorphosed Paleozoic greenstones and other magnetic rocks of the Ruby geanticline. Most of the Ruby geanticline, where it is crossed by the profile, is covered by Quaternary sedimentary deposits, but these must be thin because depth calculations show that the anomalies are produced by sources at or near the surface. This contrast in magnetic pattern between the Kuskokwim geosyncline and Ruby geanticline may be useful in delineating the western extent of the Mesozoic sedimentary rocks, although this boundary is far from linear. The Ruby geanticline extends more than 10 miles west of the Innoko River into the flat portion of the profile between this river and the Yukon anomaly; but the abrupt change in magnetic ex-

pression indicates that the rocks change character, possibly to Paleozoic sedimentary rocks, or to Mesozoic sedimentary rocks of the Koyukuk geosyncline. Thus, the western boundary of the Ruby geanticline cannot be drawn on the basis of the magnetic profile, at least in this locality.

The Yukon anomaly is the dominant feature of the western segment. Although it is flanked on either side by 20-mile stretches of flat or sloping profile, it is evident that thick sections of Mesozoic sedimentary rocks are restricted in depth and lateral extent in this part of the Koyukuk geosyncline. The Yukon anomaly indicates the presence of a zone of magnetic rock at least 15 miles wide, most of which lies east of the river. The anomaly is over one of several small areas of volcanic rock that have been mapped on the west bank of the Yukon River along the north-south portion of its course. A depth estimate on the east side of the anomaly indicates that the source is 10,000 ft below the surface. Although that is probably not a minimum value, because the anomaly is complex, it suggests that the main source is not the volcanics at the surface. A prominent anomaly of 300–400 gammas is present 60 miles to the north on the Koyukuk basin profiles (Zietz et al, 1959) where they cross the east bank of the Yukon River. Reliable depth estimates indicate the source of this anomaly is between 6,000 and 7,000 ft below the surface. The Koyukuk basin profiles delineate an area of flat magnetics west of this anomaly which narrows from a maximum width of 90 miles to 70 miles at the southernmost profile and is interpreted as a basin of thick sedimentary rocks. This flat portion may continue uninterrupted as far south as the Anchorage-to-Nome profile, where the sloping section of the profile west of the Yukon anomaly indicates a very restricted area of nonmagnetic rocks extending roughly from the Yukon River to about 20 miles east of the coast at Unalakleet. The parallelism of the anomaly with the Yukon River may indicate structural control for this part of the river's course along the eastern side of the deep sedimentary basin.

Norton Sound Magnetic Segment. The Norton Sound magnetic segment sets apart a portion of the profile which consists of numerous narrow anomalies with small to medium amplitudes and sharp gradients. Depth estimates on individual anomalies indicate that magnetic rocks lie at or near the surface. Recent work (Zietz et al, 1959) indicates that the western limit of Mesozoic sedimentary rocks of the Koyukuk geosyncline is considerably east of that shown on the tectonic map (Payne, 1955), and lies east of the Paleozoic rocks on the tip of Cape Denbigh north of Unalakleet on Norton Sound. This suggests that the first large anomaly west of Unalakleet marks the western boundary of the Koyukuk geosyncline. The smoother section of profile east of this anomaly may indicate a sedimentary section of moderate thickness, although reliable depth estimates could not be obtained here. The relation of these rocks to the sedimentary rocks just west of the Yukon River is obscure because they are separated by a zone of near-surface igneous rocks which produce the large anomaly at the east end of the Norton Sound magnetic segment. Before examination of this profile a thick sedimentary sequence of Tertiary and Quaternary age had been postulated to lie beneath the shallow waters of Norton Sound, but it is evident from the magnetic data that there is little, if any, sedimentary cover over the magnetically heterogeneous rocks of this area. These rocks may be similar to the metamorphic and igneous complex which is exposed in the Seward Peninsula, or they may consist largely of volcanic rocks of Mesozoic or later age.

CONCLUSIONS

The profile is divisible into four major segments and nine subsegments, each of which has a distinctive magnetic pattern. These magnetic units can be related to the tectonic units and in many cases provide a representative sample of the type of magnetic profile which is associated with each of the tectonic units, particularly east of the Yukon. The only tectonic units which cannot be separated by the magnetic patterns are the Tanana geanticline versus the Kuskokwim geosyncline and the Ruby geanticline versus the Koyukuk geosyncline.

The geanticlines tend to be magnetically higher and more anomalous than the geosynclines, except for the Koyukuk geosyncline. The largest anomalies are produced by the plutons of the Talkeetna geanticline, but the next largest are probably produced by a large intrusive at least a mile deep in the Koyukuk geosyncline. The Chukotskiy-Seward uplift is associated with the highly anomalous Norton Sound magnetic segment. These anomalies may be produced by thick

accumulations of volcanic rocks, by rocks similar to those of the Seward Peninsula to the north, or by both, occurring at or near the surface. The magnetic subsegment associated with the Ruby geanticline, which consists of a series of small, sharp anomalies and the larger Mt. Hurst anomaly, is the expression of Paleozoic metavolcanic rocks and, in the case of the Mt. Hurst anomaly, of a small body of mafic rock, all at or near the surface.

The parts of the profile that are flat or have only minor magnetic variations occur over the Matanuska, Alaska Range, Kuskokwim geosynclines, and over the Tanana geanticline. Even the Koyukuk geosyncline has local areas of lower magnetic profile which indicate possible areas of thick sedimentary rocks. The Tanana geanticline and the Alaska Range geosyncline consist largely of rocks with low but not negligible susceptibility. Those are probably Paleozoic and Mesozoic sedimentary rocks which have been metamorphosed to different but moderate degrees and contain minor amounts of igneous rock. The Kuskokwim geosyncline consists primarily of sedimentary rocks with minor amounts of igneous material, but the profile may not be typical in that it did not cross any of the numerous small Tertiary intrusives which occur in the geosyncline. The Matanuska geosyncline, although restricted in width in the vicinity of Anchorage, is filled with a thick section of sedimentary rocks.

In all the so-called Cenozoic basins crossed by the profile, magnetic data indicate that rocks of higher susceptibility underlie these basins at shallow depths. The Cenozoic sedimentary rocks of the Shelikof Trough and Cook Inlet basin form only a thin cover over the igneous rocks of the Talkeetna geanticline. The Minchumina lowland is probably underlain by rocks of low but not negligible susceptibility. Quaternary alluvium of the Innoko lowland overlies the rocks of the Ruby geanticline which are close to the surface. Sedimentary material is either thin or absent over the highly magnetic rocks beneath Norton Sound.

This long magnetic profile across Alaska is noteworthy because of the absence of other magnetic data for most of the area. There are obvious disadvantages in making extrapolations and depth estimates from a single profile, but the assumption that the magnetic anomalies are two-dimensional and at right angles to the profile is supported by the linearity of the tectonic trends controlling the distribution of the lithologic units. This assumption is found to be valid in the Cook Inlet survey area and to a less marked degree in the region between the Alaska Range and Norton Sound.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 727-737, 8 FIGS.

AIRBORNE GEOPHYSICAL RECONNAISSANCE IN THE CANADIAN ARCTIC ARCHIPELAGO*

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Profiles of total magnetic intensity and gamma radioactivity were obtained along a series of widely-spaced flight lines across the main tectonic regions of the Canadian Arctic Archipelago.

The interpretation of these data and the calculated depths-to-basement substantiate the recognized regional structures, confirm general geological continuity between the islands, and provide some additional structural detail. Results of particular interest are the maximum depths-to-basement in the sedimentary basins (10,000 ft or greater), the interpretation of the structure of the Precambrian arches, the extent of nonbasement igneous activity, the apparent absence of disturbed ferromagnetic rocks on the Polar Continental Shelf except near the edge where a few deep basement-type anomalies were observed, and the occurrence of anomalous radioactivity in certain sedimentary rocks on Bathurst Island. Remarkable magnetic anomalies, which in profile show a central minimum with marginal maxima, are characteristic of known gypsum domes in the Sverdrup Basin.

It is concluded that reconnaissance geophysical surveys of comparable geological regions can provide much information concerning the structure and lithology of the area. In particular, this survey reveals geophysical contrasts of significance in the planning of future investigations in the archipelago and points out a number of interesting anomalies which require further study.

INTRODUCTION

In 1955, a reconnaissance airborne geophysical survey was completed over the Arctic Archipelago in conjunction with Operation Franklin, a geological mapping program carried out by the Geological Survey of Canada. Despite the problems of operating in the remote and barren Arctic environment, a long-range Canso amphibious aircraft flew nine thousand line-miles of widely spaced profiles in a period of about two and one-half weeks. The "cobweb" flight pattern was centered on the base at Resolute on Cornwallis Island (Figure 1). The following data were recorded with a nominal terrain clearance of 800 ft and ground speed of about 120 miles per hour:

(1) total magnetic intensity, measured with an airborne fluxgate magnetometer (type ASQ-3A);
(2) total gamma radioactivity, measured with a large crystal, aerial scintillation counter (M.E.L. type AEP, 1903R, mk II);
(3) terrain clearance, measured by radio-altimeter (type AN/APN-1); and
(4) a continuous, positioning film-strip photographed with a 35 mm aerial camera.

The regional geology of the Arctic Archipelago (Figure 2) has been fairly well established (Fortier et al, in press; Thorsteinsson and Tozer, 1960; Blackadar and Fraser, 1960). The Arctic Lowlands are relatively shallow, ill-defined, remnant basins comprising lower Palaeozoic sedimentary rocks lying upon the edge of the Precambrian Shield. These basins are separated by variform, broad, basement arches. The main Palaeozoic miogeosyncline is deformed into a series of fold belts; Parry Islands, Cornwallis, Central and Northern Ellesmere. Eugeosynclinal rocks occur in both the Ellesmere Fold Belts. Metamorphic rocks of possible Precambrian age occur along the northern coast of Ellesmere Island. Mesozoic and Permo-Carboniferous strata of the Sverdrup Basin lie unconformably on the older rocks. Within this basin moderate structural deformation and basic ingneous intrusions culminate in the eastern part (Eureka Sound Fold Belt) and decline to the west. Gypsum piercement structures are proninent features, especially in the eastern half of the Sverdrup Basin. The character of the northern rim of this basin is obscured by a cover of coastal plain sediments on the northwestern islands. Beyond these lie

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FIG. 1. Location and general character of the aeromagnetic profiles, Canadian Arctic Archipelago. Base level for each segment of profile is arbitrary.

the continental shelf and the deep basin of the Arctic Ocean.

Flight lines were selected to cross the main geological regions of the archipelago with emphasis on areas where the magnetic data could most reasonably be expected to contribute useful information about local and regional structures. Features of particular interest were

(1) the depths of the sedimentary basins,
(2) the extent of known occurrences of non-basement igneous rocks,
(3) the geological significance of regional topographic lineaments along the southern coast of Devon Island and the eastern coast of Somerset Island,
(4) the nature of the Polar Continental Shelf,
(5) the structure of the Precambrian arches,
(6) the possible relationship between gypsum piercement structures and associated igneous rocks in the Sverdrup Basin, and
(7) the possible occurrence of radioactive sedimentary rocks of economic significance.

The geological significance of the aeromagnetic data has been summarized previously at the First

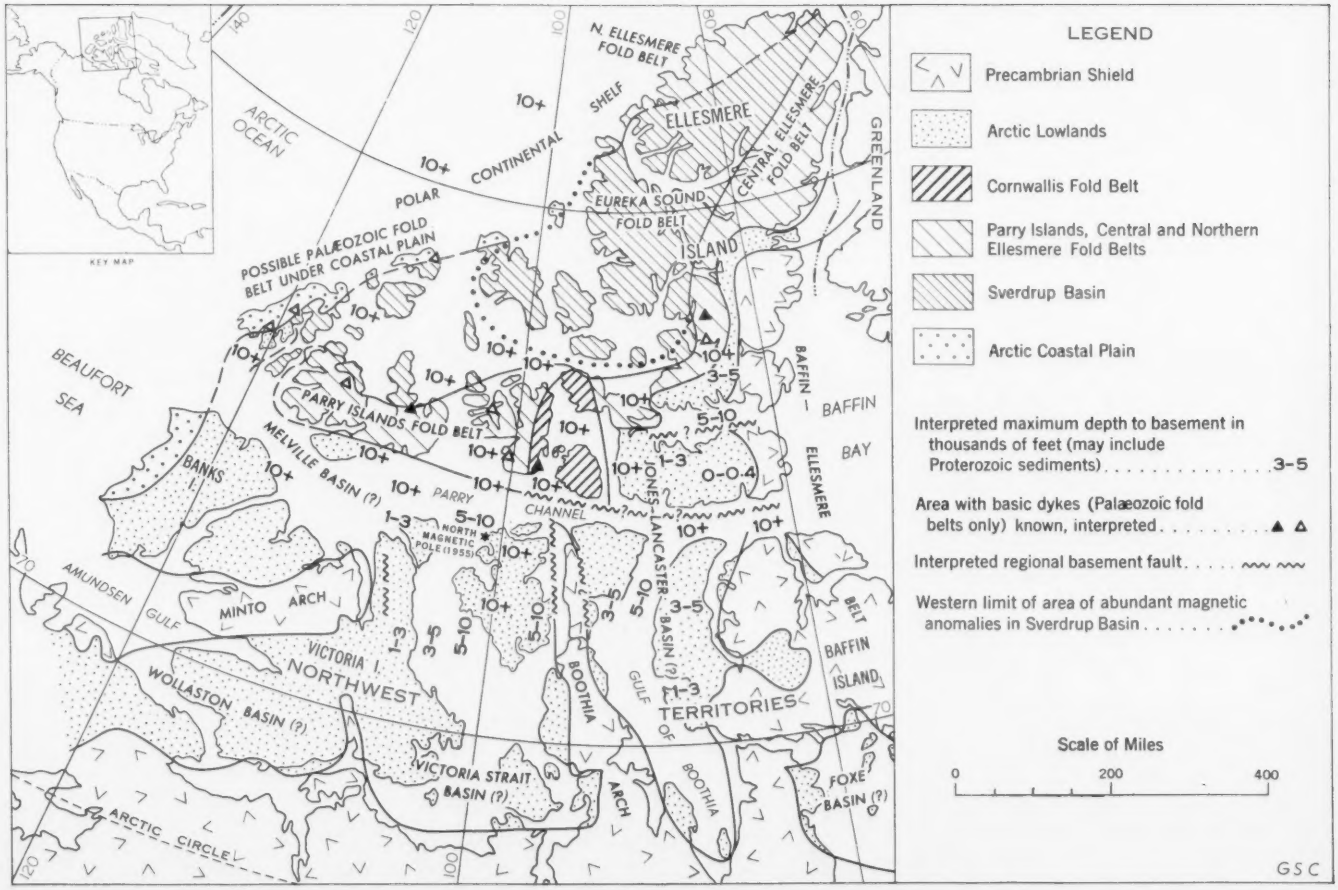

FIG. 2. Structural provinces of the Canadian Artic Archipelago and geological interpretations from the aeromagnetic data.

International Symposium on Arctic Geology (Gregory, Bower, and Morley, 1960). A more detailed consideration, comprising the geophysical profiles with interpretative notes and a descriptive text, has also been prepared for publication (Gregory, Bower, and Morley, in press). Many interesting anomalies appear on these profiles, but only a few of the more noteworthy features are discussed here.

DEPTHS OF THE SEDIMENTARY BASINS

Variations in the thickness of the stratigraphic section are of particular interest in petroleum exploration. Some information may be obtained from depth estimates calculated for magnetic anomalies judged to represent basement.[1] The depth to the magnetic body causing the anomaly was calculated from the profiles by the methods of Henderson and Zietz (1948) and Peters (1949). The usual assumptions were made. However, there is no information concerning the uniformity in intensity and direction of the rock magnetization and little information concerning the relative orientation of the magnetic body to the direction of the profile. Accordingly the calculated depths should be considered only as maximum values. It was also assumed that the depths represent the top surface of the basement. Further, as the Proterozoic strata generally are flat-lying, and thus cause no magnetic anomaly, the calculated thickness of the stratigraphic section may include Proterozoic as well as younger rocks.

The depth estimates aid in delineating the known basins (Figure 2) and suggest that maximum depths to basement are greater than 10,000 ft.

EXTENT OF NONBASEMENT IGNEOUS ROCKS

It was hoped that the aeromagnetic survey would provide information concerning the distribution of nonbasement intrusive and extrusive rocks such as were known to occur in the Proterozoic strata and in the eastern part of the Sverdrup Basin.

Local anomalies of 20 to 100 gamma were commonly encountered over Proterozoic rocks. These are attributed to dykes and disturbed sheets of basic rock. Diabase dykes with lengths of several miles and widths up to 400 ft are known to intrude such strata on Baffin Island. These carry 5 to 8 percent magnetite. Gabbroic sills and andesitic flows totalling 1,500 ft in thickness also occur in the Proterozoic section. The sills on the eastern side of the Boothia Arch carry 3 to 5 percent magnetite.

In the eastern part of the Sverdrup Basin, a unique regional feature is indicated by the distribution and variation in character of local anomalies which range from −600 to +2,400 gamma in intensity (Figure 3). The anomalies are attributed to gabbroic dykes and sills and to basaltic flows which have been deformed by folding, faulting, or intrusion of gypsum piercement structures. Gabbroic sills and dykes carrying 3 to 9 percent magnetite are common throughout the eastern part of the Sverdrup Basin while similar plutons carrying 10 to 20 percent magnetite are most common along the western coast of Axel Heiberg Island. One relatively large occurrence of massive magnetite is also known here. Several intensely strong, dyke-like anomalies observed along this coast may result from similar material (see Figure 8F).

Ellef Ringnes Island appears to be the most westerly occurrence of the anomalously high magnetic activity. This regional anomaly (see Figure 2) probably defines the extent of the Eureka Sound Fold Belt within the eastern half of the Sverdrup Basin. In contrast, very flat profiles were observed over the western part of this basin (Figure 3). However, a few local anomalies suggest the presence of thin sheets of basic rock in slightly deformed strata.

Small dyke-like anomalies of 20 to 30 gamma were occasionally recorded over the Palaeozoic fold belts (Figure 4). Some of these are related to dykes and other plutons of gabbro and olivine basalt. One gabbroic dyke carrying about 10 percent undifferentiated black oxides is several miles long and about three hundred feet in width. Only a few such plutons have been observed in the fold belts, and the magnetic data suggest that they are relatively scarce in this geological environment. Further, the otherwise generally flat aeromagnetic profiles over these fold belts show that no basic rock sheets are involved in the associated deformation. Such rocks are probably not present in the stratigraphic section.

[1] A thick complex of predominantly ferromagnetic igneous and metamorphic rocks is referred to, en masse and without geological age connotation, as *basement* in contrast to the varying thicknesses of essentially nonferromagnetic sedimentary rocks which may overlie it.

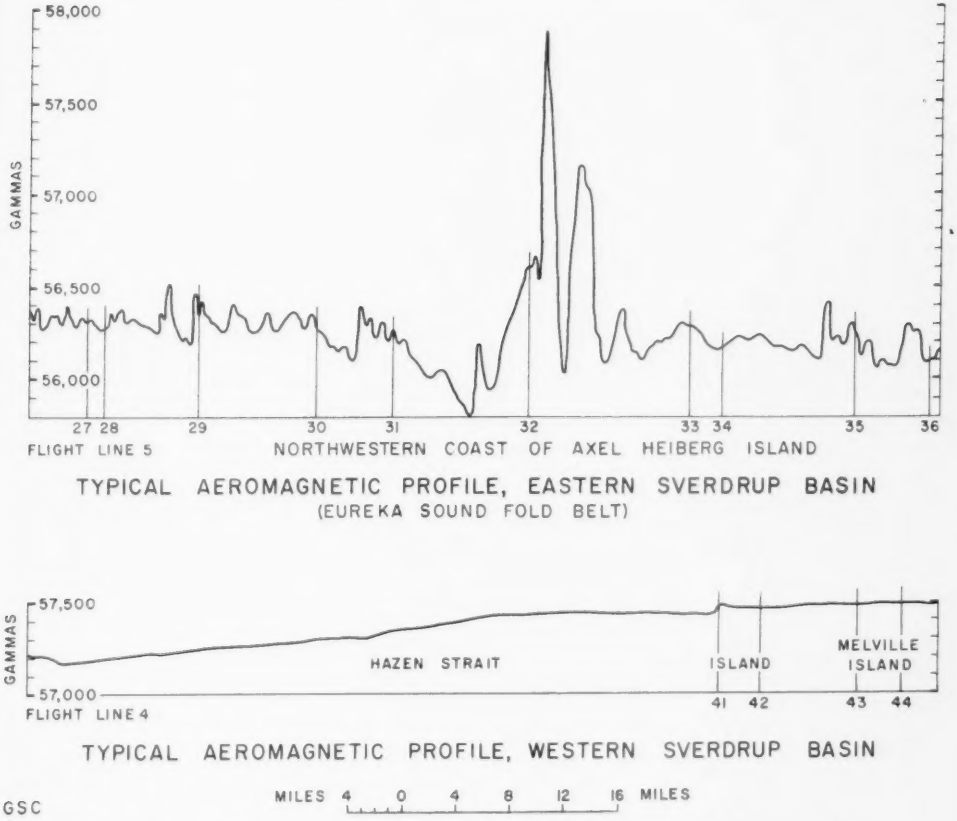

FIG. 3. Contrasting aeromagnetic profiles over the eastern and western parts of the Sverdrup Basin.

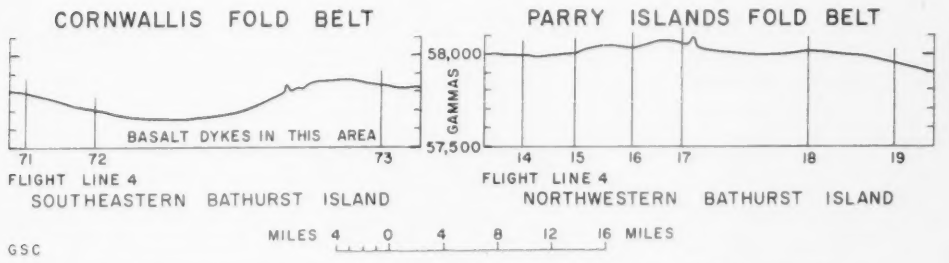

FIG. 4. Aeromagnetic profiles over Palaeozoic fold belts in the vicinity of small basic intrusions.

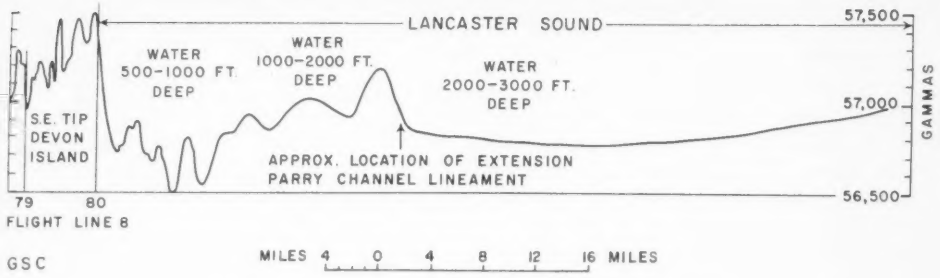

FIG. 5. Aeromagnetic profile across the Parry Channel lineament.

REGIONAL TOPOGRAPHIC LINEAMENTS

Prominent topographic lineaments occur along the southern coast of Devon Island and the eastern coast of Somerset Island. Several lines were flown across these to detect any interpretable magnetic contrasts. A notable magnetic discontinuity occurs on the profile across the Parry Channel lineament along the southern coast of Devon Island (Figure 5). North of this feature, the anomalies are sharp and strong while to the south the intensity markedly decreases and the profile becomes smooth and flat. When considered in conjunction with topographic and bathymetric data and with basement depths estimated on adjacent traverses, this profile strongly suggests that the discontinuity is the expression of a regional basement fault. As will be seen subsequently, this fault may continue westward to offset the Boothia Arch (Figure 2).

The lineament along the east coast of Somerset Island does not have magnetic evidence of a similar fault origin.

POLAR CONTINENTAL SHELF

Four traverses extended out over the Polar Continental shelf but did not reach the Arctic Ocean basin. On the aeromagnetic profiles (Figure 1) there is no evidence that basement occurs along the northwestern rim of the Sverdrup basin at depths of the order of 10,000 ft or less. However, a noncrystalline fold complex may underlie the Arctic Coastal plain. Thus, two positive dyke-like anomalies observed over these sediments on Prince Patrick Island are interpreted by analogy to the anomalies over the Palaeozoic fold belts (see p. 730) as resulting from small plutons in a similar fold belt buried under the thin veneer of sediments (Figure 2).

The positive basement-type anomalies observed near the northern tip of Axel Heiberg Island (Figure 1) suggest that crystalline rocks occur there. These may be related to the known basement rocks on northern Ellesmere Island. Similar anomalies, suggesting igneous rocks at depths of over 10,000 ft, occur at the edge of the Polar Continental Shelf. These anomalies of +200 to +700 gamma amplitude have tentatively been interpreted as indicating the westward extension of basement on northern Ellesmere Island, but they may represent separate basement or submarine volcanic features.

It is interesting to note that anomalies of similar amplitude have been observed at the edge of the continental shelf along the eastern coast of North America (Drake, Ewing, and Sutton, 1959, pp. 175, 192). In addition, a number of anomalies of roughly circular plan were found to be associated with volcanic seamounts located mainly off the edge of the shelf. The anomalies that occur at the edge of the shelf, and apparently parallel to it, are correlated with a relatively shallow basement ridge separating two deep sedimentary troughs. Drake et al suggest that these troughs may be an inner miogeosyncline under the continental shelf and an outer eugeosyncline that merges into the ocean basin. The few aeromagnetic profiles presently available across the Polar Continental shelf do not provide conclusive evidence on the presence of analogous structures.

THE PRECAMBRIAN ARCHES

Two Precambrian arches are prominent geological structures in the archipelago. The magnetic effect of basement in these arches may be subdued by a relatively thick cover of Proterozoic or younger sediments. Thus, the Minto arch

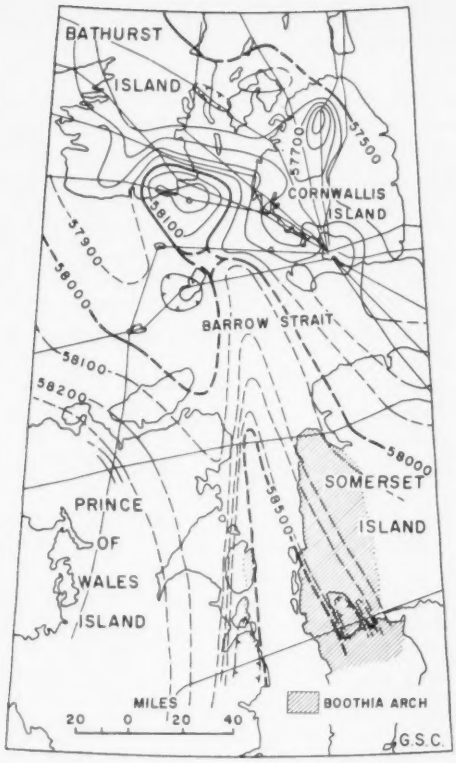

FIG. 6. Aeromagnetic map of the Boothia Arch and vicinity. Contours at 100-gamma intervals are generalized over the arch because of the wide line spacing and the complexity of the aeromagnetic data.

probably has poor geophysical expression because the Proterozoic sequence overlying the basement is over 10,000 ft thick. In contrast, the basement core of the Boothia arch is partially exposed, and the anomaly over the arch is relatively well defined on a small scale aeromagnetic map (Figure 6). The geophysical data obtained in this survey do not suggest the presence of any other unknown similar structures.

Depth estimates suggest that the Boothia arch rises about 10,000 ft above the general basement level. Archaean granites and gneisses comprise the core of the arch which is overlain by Proterozoic and lower Palaeozoic strata. On the eastern side of the arch these younger rocks are known to dip about 10 degrees northeast. The Precambrian rocks are cut by basic dykes and sills.

The observed anomaly profile corrected for regional gradient was compared (Figure 7) with the calculated anomaly (after Heiland, C.A., 1946, p. 397) for a relatively simple basement model. It is probable that the assumed model is a simplified assessment of the actual distribution of ferromagnetic material in the arch. However, the available geological data are too few to indicate which of several more complex theoretical models is most probable. Obviously a closer fit between observed and calculated anomaly profiles could be obtained by assuming a lower susceptibility contrast for the basement comprising the eastern half of the arch.

Comparison of various calculated profiles with

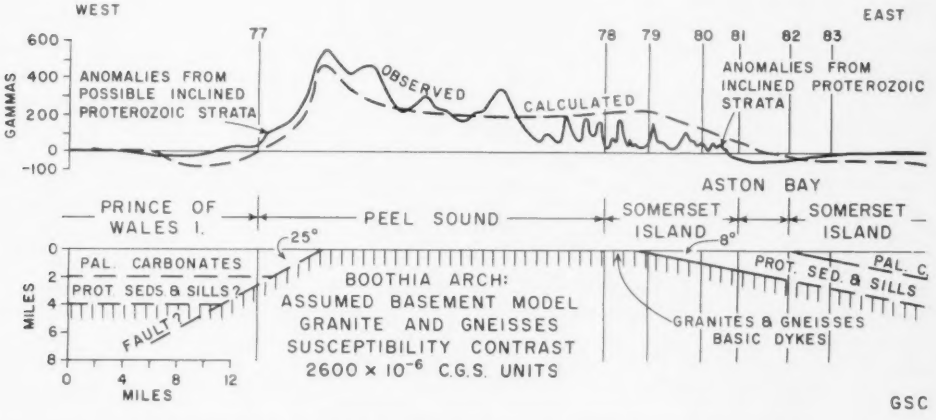

FIG. 7. Observed and calculated aeromagnetic anomaly profiles over the Boothia Arch.

the observed profile indicates that the assumed inclination of 25 degrees for the western side of the arch is a minimum. This inclination, however, may be increased up to 60 degrees and basement depths varied from two to four miles in good agreement with the observed data if Proterozoic sills are assumed to be present and upturned along this side. Thus the negative anomaly over the foot of the incline is nullified by the positive anomaly over the upturned edge of the sill sequence. Minor anomalies on the observed profile suggest that this may be true as is the case on the eastern side of the arch. However, while Proterozoic strata are known on the western side, the lithology has not been detailed to date. Because of this relatively steep inclination, the western side of the arch is interpreted as a fault. The eastern side of the arch on this profile appears to be a flatly dipping homocline, but it may be steeper and possibly faulted farther south.

Thus, in gross structure, the Boothia arch appears to be an incompletely developed horst which probably extends as far north as the southeastern corner of Bathurst Island where it terminates or plunges north. In Barrow Strait, the north end of the arch, as revealed by the aeromagnetic data (Figure 6), may be offset to the west for a distance of 10 to 20 miles along a westerly-trending fault or sharp flexure. As mentioned previously, this may be the extension of the interpreted fault along the Parry Channel lineament (Figure 2). If so, the relative movement suggested by the magnetic data is south side down (about 10,000 ft in the vicinity of Devon Island) and to the east (about 10 to 20 miles near Bathurst Island).

GYPSUM PIERCEMENT STRUCTURES

Gypsum piercement domes and diapirs intrude the Palaeozoic and younger rocks but occur primarily within the Sverdrup basin. A remarkable magnetic anomaly occurs over each of the structures traversed in this survey. In profile, the anomaly generally has a central minimum of −10 to −600 gamma bounded by maxima of +10 to +700 gamma (Figure 8). Detailed correlation of anomalies with geology is precluded by the present lack of geological detail and by the poor location control of the single profiles over these structures.

The Malloch Dome (A, Figure 8) on Ellef Ringnes Island intrudes and upturns strata which apparently contain little basic rock. The central minimum anomaly probably results from the diamagnetism of gypsum. The marginal maxima may represent upturned sediments and possibly minor volcanic flows. A few blocks of pillow lava were found within this dome. The domes on the Sabine Peninsula of Melville Island (B, C, D, Figure 8) are similar except that the maxima are slightly greater, probably as a consequence of upturned, relatively thin gabbroic sills. Blocks of gabbro occur within these domes, although no sills have been reported in the observed geological section.

The other piecement structures intrude strata in which basic rock sheets are more abundant. With the exception of the South Fiord Dome, the intruded strata are steeply upturned near the domes. The central minimum magnetic anomaly for these structures is markedly greater in magnitude than that expected from the diamagnetic effect of gypsum alone. In addition, it probably results from the induced negative anomaly from the lower edge of the upturned sills and/or from remanent magnetization effects in the disrupted sills. Similarly, the intense maxima at the edges of the structure probably result from analogous positive anomaly fields. In a few instances, the ferromagnetic rocks appear to be upturned or concentrated on only one side of these structures (e.g. the Isachsen dome).

On Axel Heiberg Island, the South Fiord Dome (G, Figure 8) intrudes but does not cause significant upturning of the strata which include relatively abundant flows and sills. The marked minimum anomaly is attributed to a greatly increased magnetization contrast between the gypsum and the igneous and sedimentary rocks intruded by the dome. The absence of upturned strata precludes the occurrence of intense magnetic maxima at the edge of the dome.

There are few magnetic data recorded in the literature for either gypsum or salt piercement structures. Salt domes in Germany and on the Gulf Coast of the United States have weak magnetic anomalies with central minima seldom exceeding 30 gamma, and bounding maxima are of the order of 5 gamma (Heiland, C.A., 1940, pp. 423–4; Hoylman, H.W., 1949). However, basic rocks are not present in the pertinent stratigraphic sections.

In Russia, strata intruded by the salt diapirs

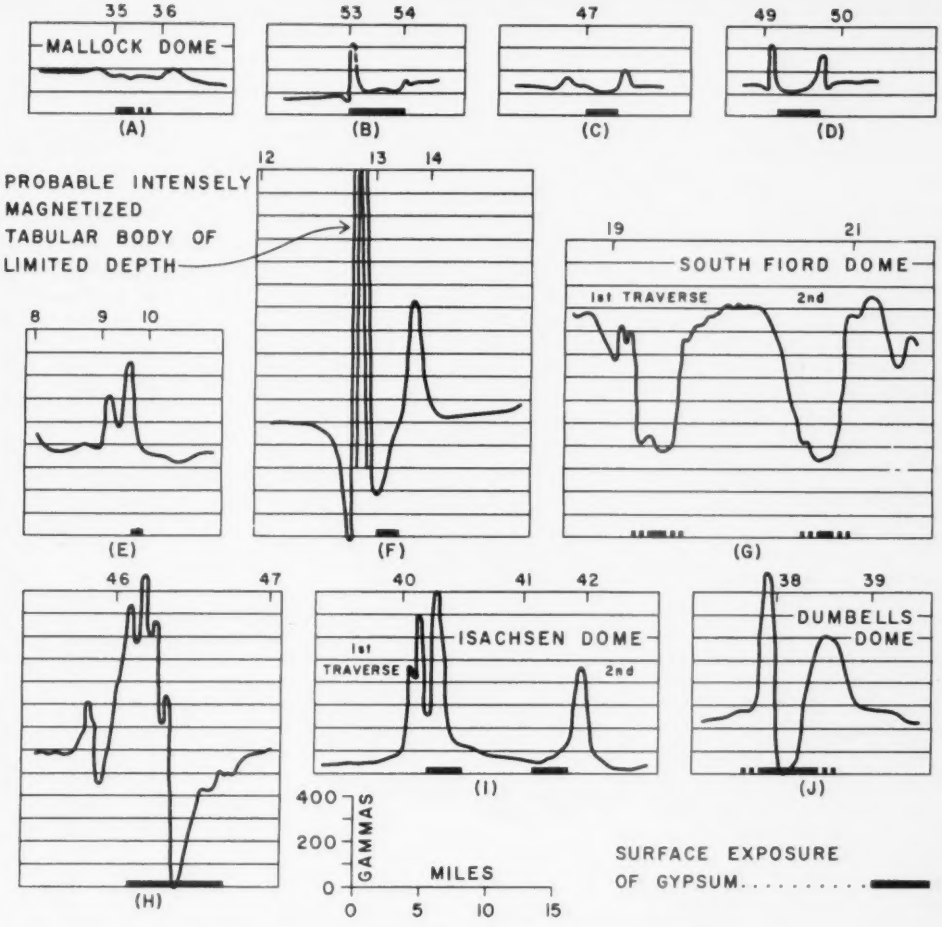

FIG. 8. Aeromagnetic anomalies over gypsum piercement structures.

of the Dneiper-Donetz Basin include diabasic sheets (Maximov, B.M., 1938; Kosygin, G.A., 1946). In the process of uplift and denudation of the salt massif, inclusions of diabase and other rocks are cemented to form a breccia capping the diapir. A published magnetic study of one such structure (The Isachki dome) reveals an irregular ring of thickly scattered, ovoid, local anomalies with positive amplitudes of 100 to 400 gamma (Andreeva, R. I., 1959). These anomalies appear to be concentrated toward the edge of the dome but may occur centrally. No marked minimum is indicated in the center although the intensity generally appears to be lower than at the edges of the dome. An aeromagnetic profile across this dome would be similar in character to that recorded over piercement structures in the Artic Archipelago. The absence of a pronounced central minimum for the Russian structures is probably the consequence of the different magnetic latitudes in which the structures occur and/or the difference in distribution of basic rock inclusions within them.

The character of magnetic anomalies over the gypsum piercement structures of the Sverdrup basin appears to vary, in a general way, with the presence and attitude of ferromagnetic rocks in the strata intruded by the gypsum. This sug-

gests that the occurrences of basic rock are mainly those of dykes and stratiform bodies within a sedimentary rock sequence which was deformed by forces attendant upon the intrusion of the gypsum.

RADIOACTIVE SEDIMENTARY ROCKS

Average-sized radioactive mineral deposits of economic value would probably not be detected in this survey because of the relatively high flight elevation. However, contrasting rock activities could be measured, and it was hoped that sedimentary rocks containing concentrations of radioelements could be recognized, especially in the fold belts where the stratigraphic section is well exposed. The aeroradiometric data were interpreted by the clearance-signal technique, i.e. by definition of the radiation absorption curve for air and for an assumed infinite area source (Gregory, 1960).

The data from the aeroradiometric survey showed that the continuation of several rock units with contrasting radioactivities could be extrapolated from known locations into adjacent unmapped areas. Of particular interest are five separate traverses across Bathurst Island during which a general, anomalously-high radioactivity was recorded over most of the sedimentary rocks. Sustained high activity was not recorded over any other area or any other rocks excepting Precambrian granites and gneisses elsewhere in the Archipelago. On Bathurst Island the major contributors of radioactivity appear to be the Okse Bay, the Bird Fiord, and the Bathurst Island formations which comprise a large proportion of the outcrop surveyed. Hence, the widespread occurrences of high radioactivity there. The magnitude of the rock activity contrasts measured aeroradiometrically is supported by radiometric comparison of a few representative rock specimens (Gregory, Bower, and Morley, in press). While the uranium content of these specimens is very low (about 0.003 percent equivalent U_3O_8), the possibility of the occurrence of radioactive mineral deposits in these formations, and especially in the Okse Bay sandstone, should not be overlooked.

CONCLUSIONS

(1) This reconnaissance geophysical survey has revealed the existence, within the Canadian Arctic Archipelago, of significant magnetic and radiometric contrasts.

(2) Efficient, detailed airborne geophysical surveying could be achieved by utilizing the most recent techniques for aerial surveying of featureless terrains and by having a selection of areas to survey as the vagaries of local weather permit.

(3) Interpretation of the observed geophysical data provides much useful information concerning the structure and lithology of the region, and similar results might be expected from reconnaissance surveys of comparable geological regions.

(4) The Boothia arch and the gypsum piercement structures, in particular, have very interesting magnetic anomalies. Further detailed geophysical investigations of these and similar geological structures may clarify their origin and provide geological information that is of both scientific interest and economic importance.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 738–753, 25 FIGS.

WAVE-FRONT CHARTS AND THREE DIMENSIONAL MIGRATIONS*

ALBERT W. MUSGRAVE†

A computer is required to calculate the complex wave-front charts which are needed in many areas. On a medium size computer wave-front charts can be constructed using up to 40 layers. Each layer can be a constant velocity or can start with any velocity and have an increase in velocity with vertical time. These wave-front charts may be automatically plotted for use in migration in a vertical plane. At the same time that the wave-front chart is being obtained, a list may be made which shows the depth and offset for each reflection time and stepout value. This migration list may be used to migrate values from time maps in three dimensions. Before migrating, these time maps should have contours of all time values even though overlapping occurs as on buried foci of sharp synclines. Thus, it is a simple matter to make a migrated depth map from any time map regardless of the crookedness and discontinuity of the profiles or the lack of cross-line control.

INTRODUCTION

The geophysicist refers to the leading surface of the seismic disturbance as the wave front. The wave front is a spheroidal surface expanding from the shotpoint with increasing time. In isotropic media, raypaths are imaginary lines constructed perpendicular to the wave front at all times. The wave front is distorted from a perfect sphere by velocity changes in the earth through which it propagates.

Wave-front charts are made by the calculation of wave-front intersections, at a series of time increments, with a chosen set of raypaths in a vertical plane through the origin. In order to perform this calculation, assumptions about the subsurface velocity configuration must be mathematically describable. Before electronic computers were available, velocity configurations had to be limited to those which could be represented by simple mathematical functions.

VELOCITY ASSUMPTIONS

Velocity may vary in both the vertical and horizontal directions. Wave-front charts are usable only in areas where velocity does not vary horizontally or varies in particular ways as described in the author's doctorate thesis (Musgrave, 1952).

Horizontal Variations

Figure 1 shows the two basic isovelocity configurations as taken from this thesis. The diagram on the right shows an area where isovelocity surfaces are parallel to or equidistant from the reflector. Velocity has a horizontal gradient as a result of vertical changes, so wave-front charts and migration lists are difficult to use. Raypaths are straight lines in this case and the velocity changes near the origin. The special case of having small variations with depth will allow the use of fairly simple charts and lists. The diagram on the left shows an area where isovelocity surfaces are parallel to the datum plane. If the datum plane is horizontal, velocity has no horizontal gradient and a wave-front chart will resolve the two dimensional dip profiles. A migration list will resolve the dip in three dimensions.

Vertical Variations

Vertical velocity distribution in the earth is determined by velocity surveys. This determination can be made more accurately from continuous velocity logs. Velocity variations in the vertical direction are much more severe than in the horizontal direction. Several continuous functions have been used to approximate various vertical configurations. Electronic computer programs can use discontinuous mathematical functions which represent the vertical distribution of velocity with any amount of detail required. Figure 2 shows a time versus velocity plot for three velocity functions. Average velocity is shown by solid lines and instantaneous velocity is shown by

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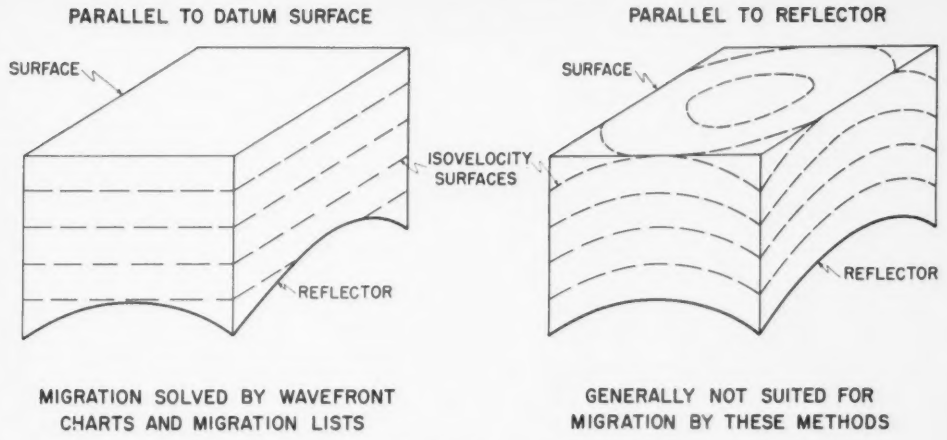

FIG. 1. Two general classifications of isovelocity configurations.

dashed lines. The curved lines represent a linear increase with depth function that is the basis of the wave-front chart shown in Figure 3. The straight lines represent a linear increase with time function (based on the same shallow velocity control as used for the linear with depth function) that is the basis of the chart in Figure 4. Finally, the lines originating at 6,800 ft/sec represent a two-layer discontinuous function that is the basis for the chart shown in Figure 5. The two layers have different accelerations or rates of velocity change.

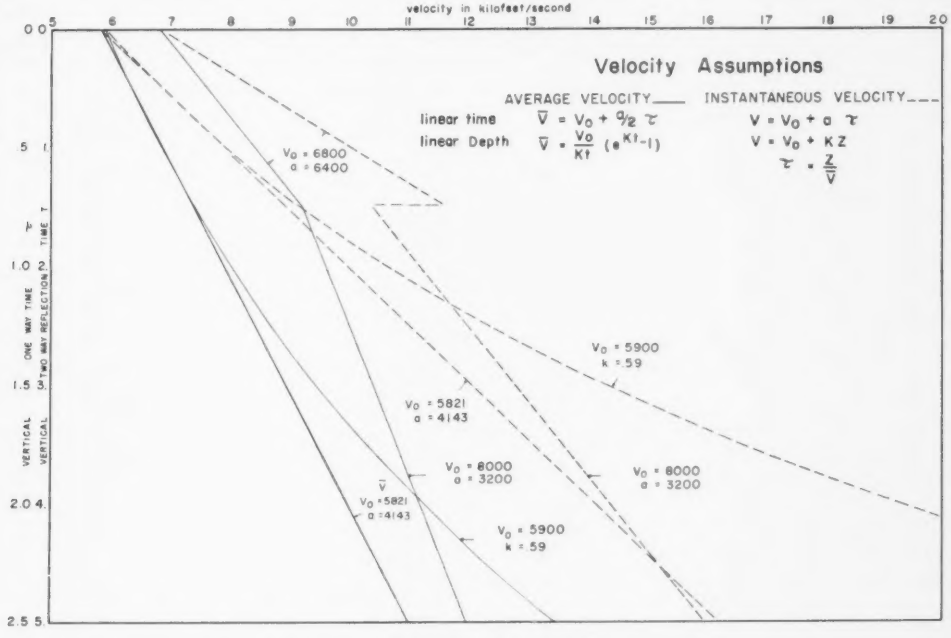
velocity in kilofeet/second
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0.0
1.0 2.
1.5 3.
2.0 4.
2.5 5.
VERTICAL ONE WAY TIME TWO WAY REFLECTION TIME T
Velocity Assumptions
AVERAGE VELOCITY
INSTANTANEOUS VELOCITY
linear time $\bar{V} = V_0 + \frac{a}{2}\tau$ $V = V_0 + a\tau$
linear Depth $\bar{V} = \frac{V_0}{Kt}(e^{Kt}-1)$ $V = V_0 + KZ$
$\tau = \frac{Z}{\bar{V}}$
V_0 = 6800 a = 6400
V_0 = 5900 k = .59
V_0 = 5821 a = 4143
V_0 = 8000 a = 3200
V_0 = 8000 a = 3200
$\bar{V}$ V_0 = 5821 a = 4143
V_0 = 5900 k = .59

FIG. 2. Time vs velocity plot for three velocity configurations.

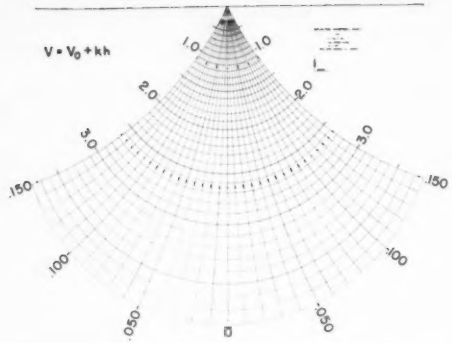

FIG. 3. A reflection wave-front chart made on the basis of a linear increase of velocity with depth.

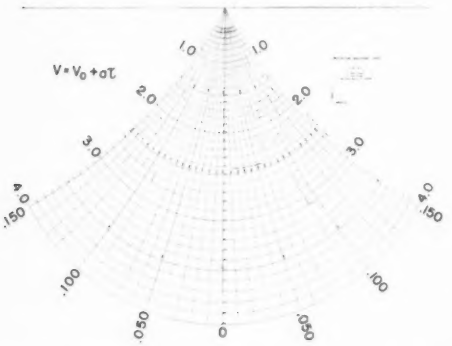

FIG. 4. A reflection wave-front chart made on the basis of a linear increase of velocity with vertical time.

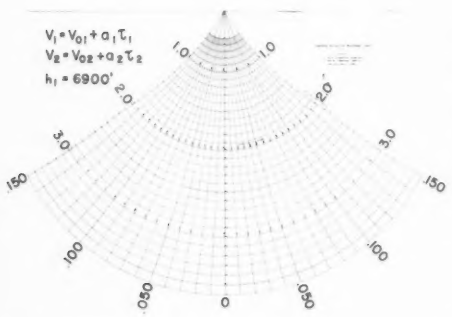

FIG. 5. A wave-front chart made using two layers with a different increase of velocity in each layer.

LINEAR INCREASE OF VELOCITY WITH TIME ASSUMPTION

Although the linear-with-depth function is more popular because of its simplicity, the linear-with-time function has several advantages as the basis of wave-front charts. Some of these advantages are: (1) a better empirical fit to actual velocity data is possible, (2) multilayer charts can be constructed, and (3) the constants are more easily determined than for a linear-with-depth function.

First Layer

Figure 6 shows a diagram of a raypath and the derivation of the equations used in calculating wave-front charts. The integral equations for time and distance are derived from Snell's law and trigonometric relations. Substitution of the linear increase of velocity with time assumption into these general equations gives the parametric equations for time, offset, and depth. Notice that the time along any raypath is directly proportional to the dip α, that the parameter θ equals 2α, and that the equations for offset and depth are those of a right cycloid whose axes are shifted by amounts x_0 and h_0.[1] A right cycloid is defined as a curve generated by a point on a circle rolling along a straight line as shown in Figure 7. θ is the angle of revolution of the circle and R is its radius. The circle generates the raypath by rolling along a line on the bottom side of a plane situated parallel to the datum plane and a distance above it which is coincident with zero on the velocity scale of the layer. The times and coordinates of depth and offset starting from zero for each wave-front-raypath intersection must be calculated. The values must be calculated all the way down to the depth of occurrence of the maximum velocity which is denoted by subscripts whose first character is M. The portion above the point of occurrence of minimum or beginning velocity is subtracted. The subtracted quantities are denoted by symbols having subscripts whose first character is zero. The second character of the subscripts refers to the layer being used. The character s denotes length of the subsurface coverage.

[1] In the oral presentation of the paper Dr. F. A. Van Melle brought to the author's attention that this curve is the same as the curve of the quickest descent of a particle under the influence of gravity and is called the brachistochrone.

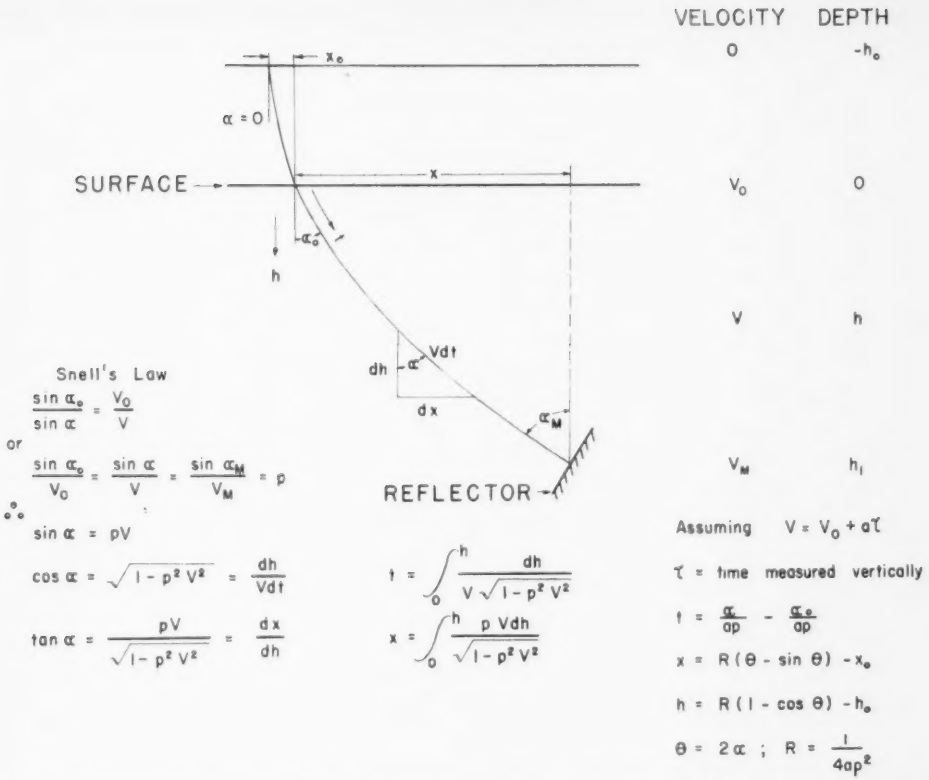
VELOCITY DEPTH
0 -h₀
SURFACE
α = 0
x₀
x
V₀ 0
h
V h
Vdt
dh
dx
Snell's Law
sin α₀ / sin α = V₀ / V
or
sin α₀ / V₀ = sin α / V = sin α_M / V_M = p
sin α = pV
cos α = √(1 − p²V²) = dh / Vdt
tan α = pV / √(1 − p²V²) = dx / dh
t = ∫₀ʰ dh / V√(1 − p²V²)
x = ∫₀ʰ p Vdh / √(1 − p²V²)
REFLECTOR
V_M h₁
Assuming V = V₀ + aτ
τ = time measured vertically
t = α/ap − α₀/ap
x = R(θ − sin θ) − x₀
h = R(1 − cos θ) − h₀
θ = 2α ; R = 1/4ap²

FIG. 6. The general relationships of time, offset, and depth for any continuous velocity function and specifically those for the assumption that velocity increases linearly with time.

Second Layer

Figure 8 shows the raypath entering the second layer, designated by subscripts whose second character is 2. This layer may have any velocity at its top and any rate of velocity increase, or acceleration, including zero. A change in these velocity properties from those of the first layer will change the size of the circle generating this second portion of the raypath. The height of the plane along which it rolls will also be changed. The plane would be repositioned at the height of zero on the velocity scale of the second layer. The raypath is made to maintain continuity across the interface by adding its second layer times and coordinates to the maximum corresponding values found on the raypath in the first layer.

COMPUTER PROGRAM

A continuation of this process is used in our IBM 650 program to carry out the tedious calculations required when velocity distributions become complex. Up to 40 layers can be handled by the program. Data input to the program for control is (1) a chart number, (2) the number of layers, (3) whether a refraction (1 way time) or reflection (2 way time) chart is to be calculated, (4) whether either or both list and plot are required, (5) whether special raypaths need to be calculated, and (6) information about plot symbols.

Data input to the program for calculation include (1) the initial and final raypath, (2) the raypath increment, (3) the minimum and maximum depth, (4) the maximum offset, (5) the increment of travel time, (6) the initial and final velocities, (7) the acceleration of each layer, (8) the depth of each layer, and (9) the scale factor for plotting if a plot is required.

The program calculates the coordinates for depth and offset of the intersection of each ray-

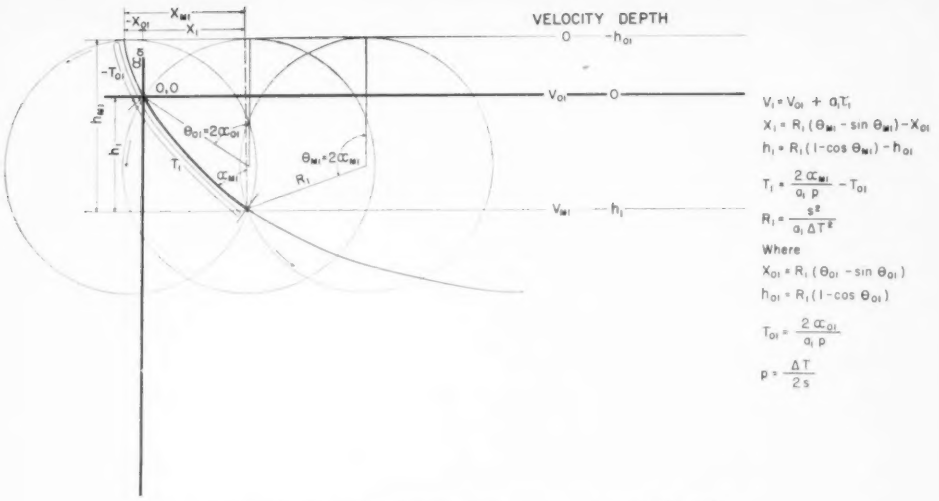

FIG. 7. Diagram and mathematical relations used to calculate the cycloidal raypaths through the first layer.

path with each increment of travel time within the limits of the maximum values. The output can be both a plot and a list card for each intersection calculated. Special plot symbols are assigned to intersections falling on designated raypaths and wave fronts, usually those having values that are multiples of five. In addition to the incremented raypaths, special raypaths may be calculated which are incident on each interface at very nearly the critical angle for the final velocity of each layer. These are needed to control the shape of the wave front near the inter-

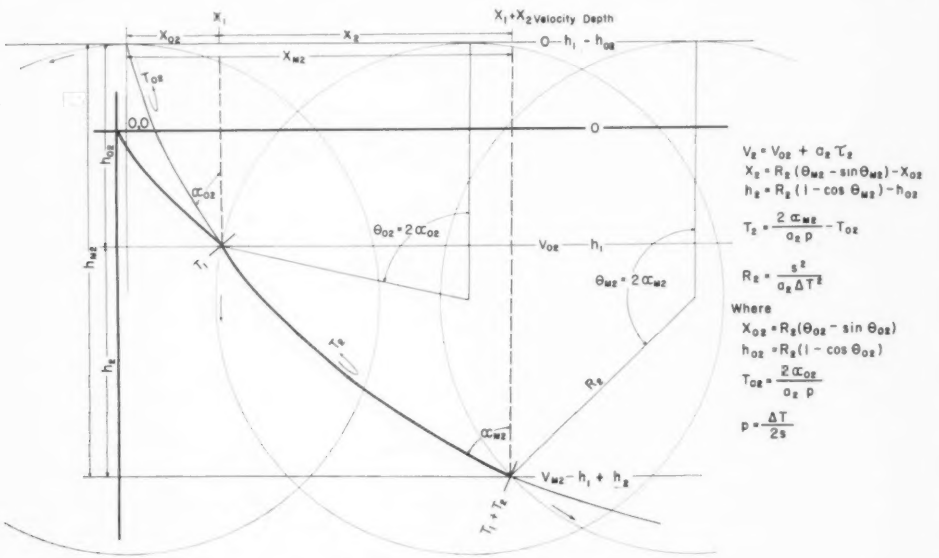

FIG. 8. Diagram and mathematical relations used to calculate the cycloidal raypath on through the second layer.

face. The raypaths used here are those defined by the ΔT across a chosen unit of length of subsurface coverage.

EXAMPLE OF COMPLEX WAVE-FRONT CHART

Figure 9 shows a plot of time versus velocity in a fairly complex configuration. This configuration was used to calculate a wave-front chart, a portion of which is shown in Figure 10. This chart was plotted by listing the IBM 650 output plot cards on an off-line IBM 407 tabulating machine. The platen drive of the 407 is modified for 10 lines to the inch, so plotting accuracy is plus or minus 1/20th of an inch. Accuracy can be improved by plotting to a large scale and photographically reducing the plots to the desired scale. The final wave-front chart is shown in Figure 11. The final plotting accuracy is plus or minus 1/40th of an inch or less than one millimeter.

Values of depth and offset from the list cards can be read directly into a Benson-Lehner Model S electroplotter. A plot prepared in this way is shown in Figure 12.

Both plots of this chart were calculated using the same velocity function but different raypath increments or lengths of subsurface coverage. This illustrates the utility of the program in adapting the charts to changes in length of the geophone cable used by the field crew.

Even though raypaths and wave fronts are not constructed with continuous lines, these charts are quite usable for plotting dips from reflection seismic records. The only manual drafting needed is the addition of identification and labels for the raypaths and the wave fronts.

MIGRATION BY WAVE-FRONT CHARTS

Reflection wave-front charts are used to plot depth cross-sections from the time and step out, or ΔT, taken from seismic records along a line of profile. The depth section can be made in two ways from split continuous records.

First Method

When using the long trace-to-long trace method, the cross-section paper is placed over the chart so that the shotpoint coincides with the

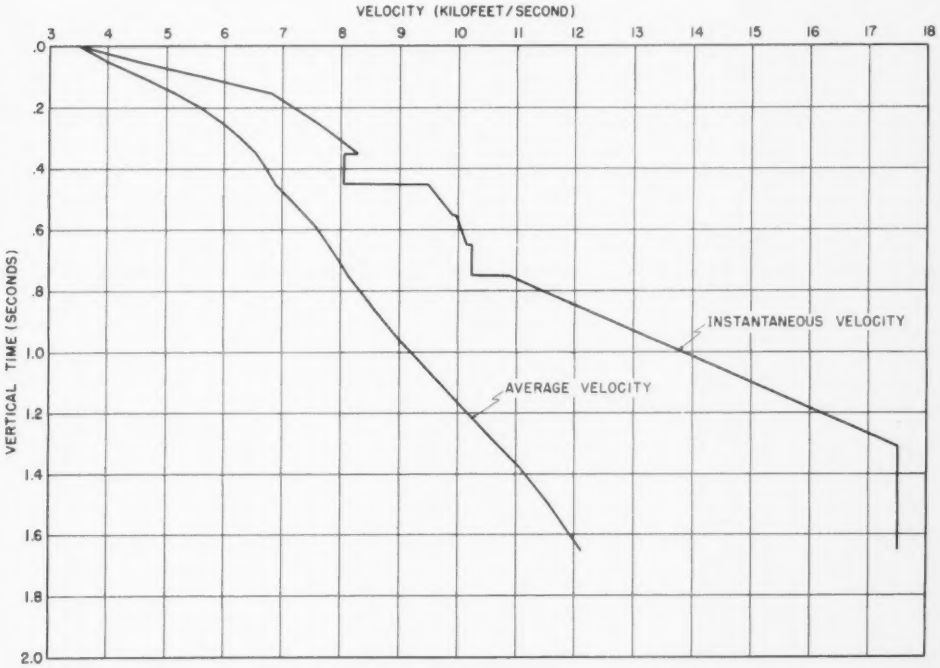

FIG. 9. Velocity configurations for a complex wave-front chart.

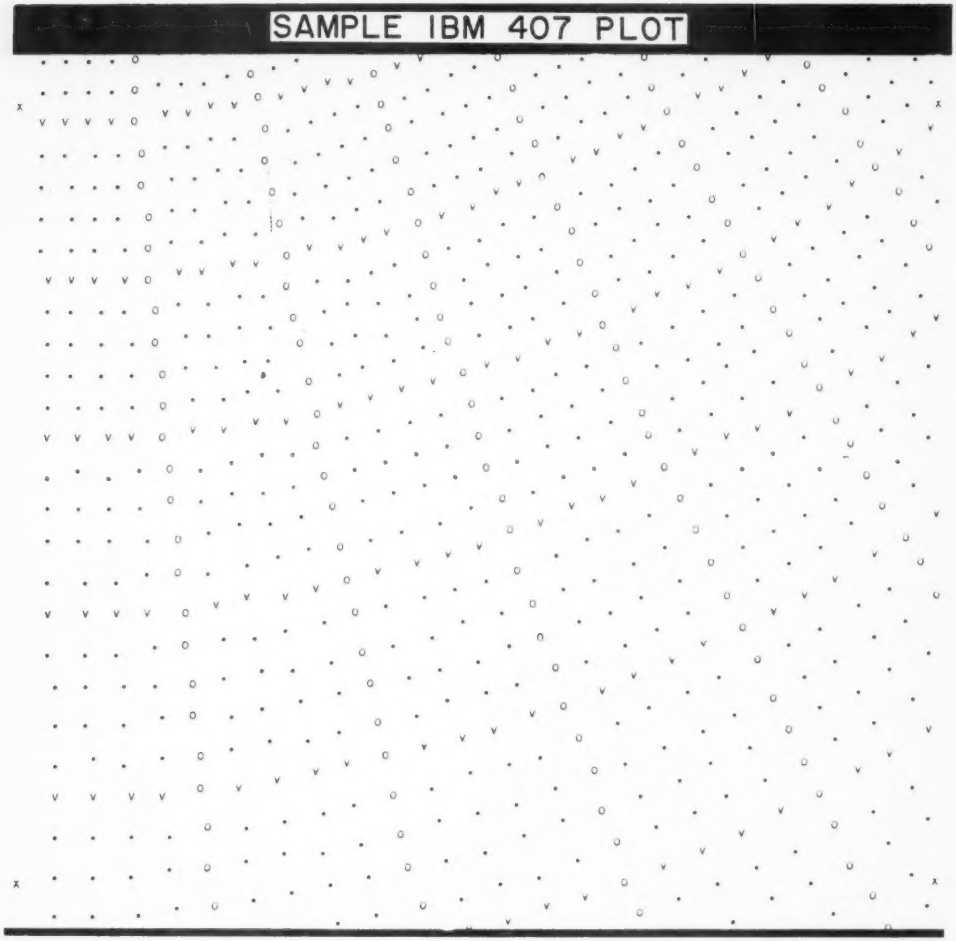

FIG. 10. A detailed portion of the wave-front chart shown in Figure 11 as plotted on the IBM 407.

origin of the chart. The travel time is taken as the corrected reflection time of the center traces. The ΔT is taken as the difference in corrected reflection times of the end traces. These two values locate the mid-point of the reflecting segment on the chart. The reflection segment is drawn tangent to the wave front with a length equal to one-half the distance between end traces. If irregular spread lengths are encountered, the end traces must be corrected for normal moveout and the ΔT normalized to the chart. This normalization is done by multiplying the moveout corrected ΔT by the ratio of the length of the spread to the unit of length chosen for the chart.

Second Method

When using the center-to-center method, the cross-section paper is placed over the chart so that its origin is midway between two shotpoints. Travel time is taken as the average of the corrected center trace times on the records taken at these shotpoints. The difference between the center trace times is the ΔT. These two values locate the reflecting segment on the chart. The segment is drawn as before with a length equal to the shotpoint spacing. If this spacing is not equal to that for which the chart was calculated, the ΔT must be normalized as described before, but no correction for normal moveout is required.

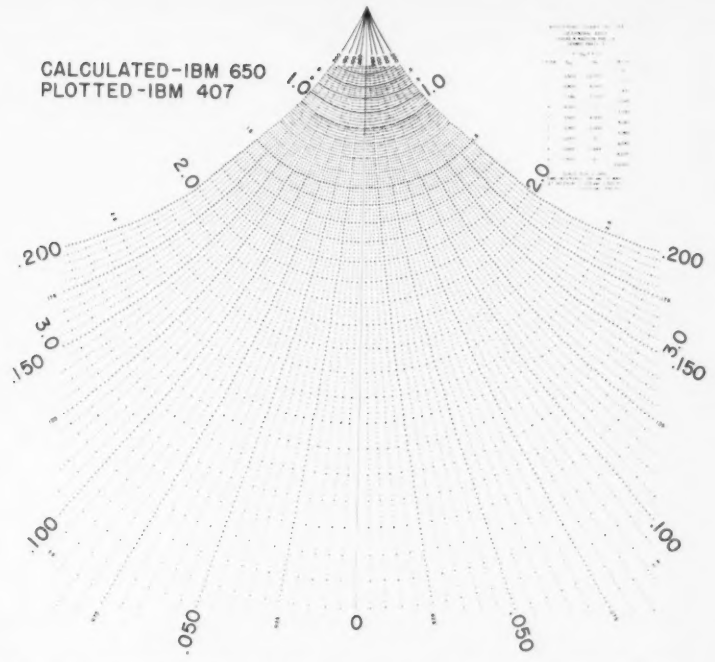

FIG. 11. A complete wave-front chart plotted by the IBM 407 for the velocity configuration shown in Figure 9 and for a subsurface coverage equal to 1,320 ft.

The advantage of the long trace-to-long trace method is that the ΔT is taken from a single record and is not affected by hole lag, variations in time break and uphole time, filter corrections, and ghost effect.

The advantage of the center-to-center method is that no normal moveout correction is necessary and that the datum correction can be calculated more easily.

EXAMPLE OF WAVE-FRONT CHART MIGRATION

Figure 13 shows a section where reflection times are plotted vertically below the shotpoints where they are observed. A record section would serve equally well. Any length of reflection segment may be migrated by normalizing the ΔT. These time data are migrated by a wave-front chart into the depth section shown in Figure 14. With some knowledge of the geology of the area and dips of shallower reflections, the depth section might be interpreted as shown in Figure 15. All of the time data turns out to be reflected from one horizon, the data having three buried foci and a point of diffraction. A buried focus of a reflection results from a syncline whose radius of curvature is smaller than the radius of curvature of the wave front.

MIGRATION LISTS

Three dimensional migration may be accomplished by using a printed list from the list cards output by the IBM 650 program. The information punched in the list cards is chart number, raypath, interface, travel time, depth, and offset. These cards can be sorted and listed as shown in Figure 16. The sort for this list was in order of raypath for each wave front or travel time. An alternate list is made by sorting in order of travel time for each raypath. Pages of this type of listing are put together to form the composite list shown in Figure 17. This list is most useful in resolving dip in three dimensions.

It is necessary to have an identifiable reflection. Before the list can be used, a time map must be made of this reflection. All possible reflection times must be picked and put on the map even

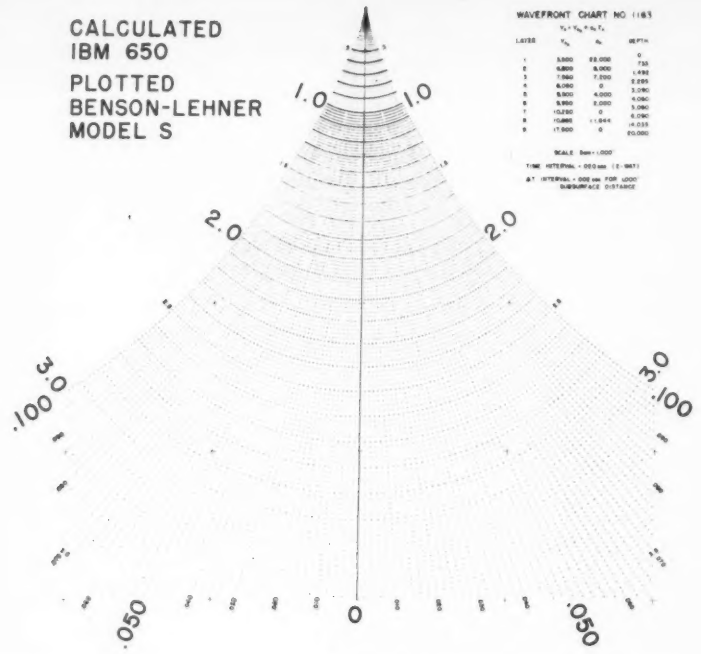

FIG. 12. A wave-front chart plotted by the Benson-Lehner Model S electroplotter using the velocity configuration shown in Figure 9 and a subsurface coverage equal to 1,000 ft.

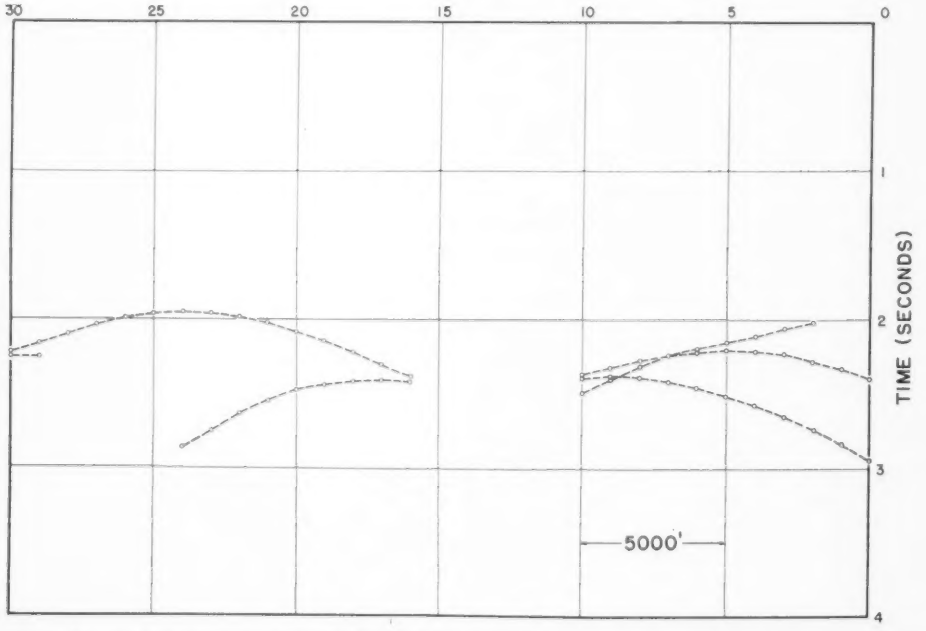

FIG. 13. A time cross-section made from reflection records in a complex area. A record section may be used just as well or better for this purpose.

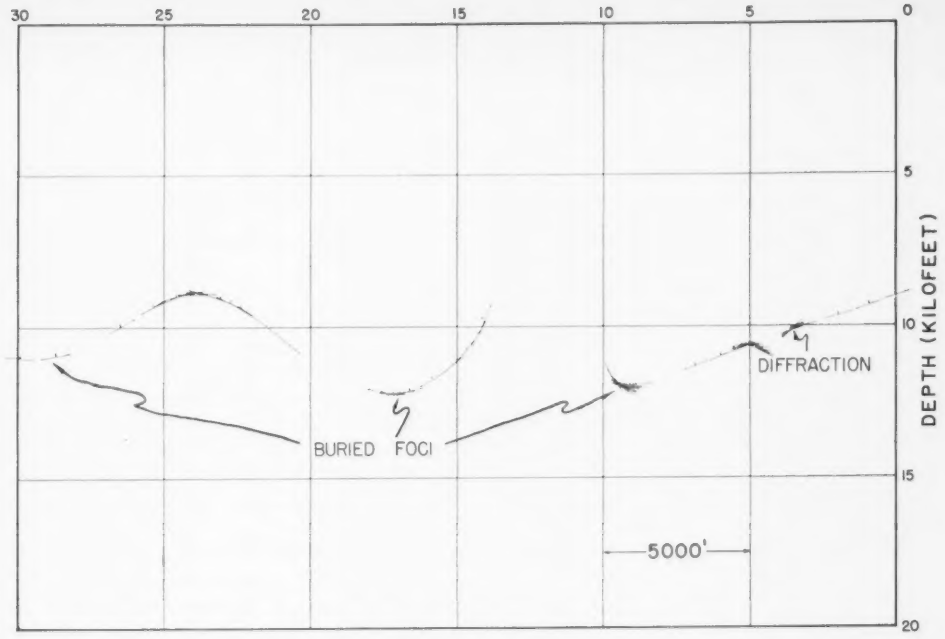

FIG. 14. A migrated depth section from the times shown in Figure 13.

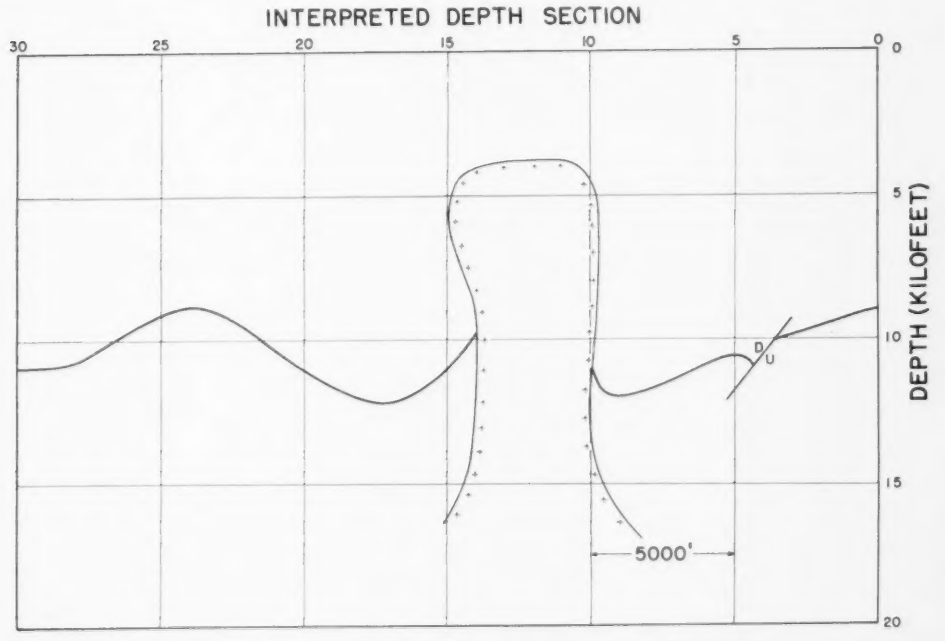

FIG. 15. An interpretation of the migrated section shown in Figure 14.

CHART NO.	RAYPATH IN SECS. PER M FT. OF HORZ. DIST.	INTER PACE	TRAVEL TIME SECONDS	DEPTH FEET	OFFSET FEET
1166	.002000	14	2.8600	11.321	93
1166	.004000	14	2.8600	11.321	187
1166	.006000	14	2.8600	11.320	280
1166	.008000	14	2.8600	11.312	372
1166	.010000	14	2.8600	11.309	486
1166	.012000	14	2.8600	11.304	558
1166	.014000	14	2.8600	11.296	651
1166	.016000	14	2.8600	11.289	744
1166	.018000	14	2.8600	11.280	837
1166	.020000	14	2.8600	11.270	929
1166	.022000	14	2.8600	11.259	1.022
1166	.024000	14	2.8600	11.248	1.117
1166	.026000	14	2.8600	11.238	1.208
1166	.028000	14	2.8600	11.220	1.299
1166	.030000	14	2.8600	11.206	1.389
1166	.032000	14	2.8600	11.189	1.480
1166	.034000	14	2.8600	11.173	1.575
1166	.036000	14	2.8600	11.156	1.665
1166	.038000	14	2.8600	11.137	1.756
1166	.040000	14	2.8600	11.119	1.844
1166	.042000	14	2.8600	11.097	1.937
1166	.044000	14	2.8600	11.073	2.026
1166	.046000	14	2.8600	11.055	2.115
1166	.048000	14	2.8600	11.027	2.207
1166	.050000	14	2.8600	11.004	2.295

FIG. 16. A representative portion of the IBM calculated migration list, sorted in order of increasing raypath or stepout for each time, showing depth and offset for each time and stepout.

though the reflection overlaps in synclines and appears several times on the same record. These overlaps may not be meaningful until they are migrated.

EXAMPLES OF THREE-DIMENSIONAL MIGRATION

Figure 18 shows a time map of an anticline made with values from records taken at all of the shotpoints indicated on the grid. The migrated depth map is made by reading travel times at the shotpoints and interpolating the stepout across the distance for which the list is calculated, measured normal to the time contours. One such time and offset is indicated on the map. These values serve as entry to the migration list and determine the values of depth and offset from Figure 17. Although straight traverse lines have been used for this synthetic example, the migration system is of even more benefit if cultural and/or topographic features require shooting crooked lines.

Figure 19 shows the completed depth map after all points have been migrated. Notice how much the depth points converge on the anticline in the areas of steep dip.

It is interesting to see what happens with a syncline of this same shape. Figure 20 shows a cross-section across the east-west axis of a shallow and a deep syncline. The synclines are narrower in time than in depth. The buried focus effect of the deep syncline causes some time overlap. Figure 21 shows a cross-section across the north-south axis of these same synclines. The steeper dips in this direction caused considerable time overlap which shows the buried focus effect more prominently. Note that the overlap increases with the sharpness of the syncline and with greater depth.

Figure 22 shows the time map of the shallow syncline. The steeper north-south dip causes more squeezing of the contours than the more gentle east-west dip. The small amount of time overlap, because of the buried focus, is shown in the center of the map.

Figure 23 shows a depth map of the syncline

STEPOUT (ΔT) →	0		.020		.040		.060		.080		.100	
TRAVEL TIME SECONDS	DEPTH FEET	OFFSET FEET	DEPTH FEET	OFFSET FEET	DEPTH FEET	OFFSET FEET	DEPTH FEET	OFFSET FEET	DEPTH FEET	OFFSET FEET	DEPTH FEET	OFFSET FEET
1.8800	8.368		8.316	793	8.162	1.568	7.909	2.311	7.570	3.014	7.145	3.656
1.9000	8.500		8.447	810	8.287	1.602	8.027	2.360	7.678	3.076	7.241	3.728
1.9200	8.633		8.578	828	8.413	1.636	8.145	2.409	7.786	3.138	7.337	3.802
1.9400	8.767		8.710	846	8.541	1.671	8.265	2.460	7.895	3.202	7.434	3.876
1.9600	8.902		8.844	864	8.669	1.706	8.385	2.511	8.005	3.267	7.531	3.952
1.9800	9.038		8.979	882	8.799	1.743	8.506	2.563	8.115	3.333	7.628	4.028
2.0000	9.176		9.114	901	8.929	1.779	8.628	2.616	8.226	3.400	7.726	4.106
2.0200	9.315		9.251	920	9.061	1.817	8.751	2.670	8.337	3.468	7.825	4.185
2.0400	9.455		9.389	940	9.195	1.855	8.874	2.725	8.449	3.537	7.921	4.265
2.0600	9.596		9.529	960	9.327	1.893	8.999	2.781	8.561	3.607	8.020	4.348
2.0800	9.738		9.669	980	9.461	1.933	9.124	2.837	8.674	3.678	8.118	4.429
2.1000	9.882		9.811	1.000	9.597	1.972	9.250	2.895	8.787	3.750	8.217	4.513
2.1200	10.027		9.953	1.021	9.733	2.013	9.376	2.953	8.901	3.824	8.315	4.597
2.1400	10.173		10.097	1.042	9.871	2.054	9.504	3.012	9.015	3.898	8.414	4.683
2.1600	10.320		10.242	1.064	10.009	2.096	9.632	3.072	9.130	3.973	8.514	4.770
2.1800	10.468		10.388	1.085	10.149	2.139	9.761	3.133	9.245	4.050	8.613	4.859
2.2000	10.618		10.535	1.108	10.289	2.182	9.890	3.195	9.361	4.128	8.712	4.948
2.2200	10.768		10.684	1.130	10.430	2.226	10.021	3.258	9.477	4.206	8.812	5.039
2.2400	10.920		10.833	1.153	10.573	2.270	10.152	3.322	9.593	4.286	8.912	5.131
2.2600	11.073		10.984	1.176	10.716	2.315	10.284	3.387	9.710	4.367	9.011	5.224
2.2800	11.228		11.135	1.200	10.860	2.361	10.416	3.452	9.828	4.449	9.111	5.318
2.3000	11.383		11.288	1.224	11.006	2.408	10.550	3.519	9.946	4.533	9.211	5.413
2.3200	11.540		11.442	1.248	11.152	2.455	10.684	3.587	10.066	4.617	9.311	5.510
2.3400	11.697		11.597	1.273	11.299	2.503	10.818	3.655	10.182	4.702	9.411	5.608
2.3600	11.856		11.754	1.298	11.447	2.551	10.954	3.725	10.301	4.788	9.511	5.707
2.3800	12.016		11.911	1.323	11.597	2.601	11.090	3.795	10.421	4.877	9.611	5.807
2.4000	12.178		12.070	1.348	11.747	2.651	11.227	3.866	10.540	4.965	9.711	5.908
2.4200	12.340		12.229	1.375	11.898	2.702	11.364	3.939	10.660	5.055	9.811	6.011
2.4400	12.504		12.390	1.402	12.050	2.753	11.502	4.012	10.781	5.146	9.911	6.114
2.4600	12.669		12.552	1.428	12.202	2.805	11.641	4.087	10.901	5.239	10.011	6.219
2.4800	12.835		12.715	1.456	12.356	2.858	11.781	4.162	11.022	5.332	10.111	6.325
2.5000	13.002		12.879	1.483	12.511	2.912	11.921	4.238	11.143	5.427	10.210	6.431
2.5200	13.171		13.044	1.512	12.667	2.966	12.061	4.316	11.265	5.522	10.310	6.542
2.5400	13.340		13.210	1.540	12.823	3.021	12.203	4.394	11.387	5.619	10.410	6.651
2.5600	13.511		13.378	1.569	12.981	3.077	12.345	4.473	11.509	5.717	10.509	6.761
2.5800	13.683		13.546	1.598	13.139	3.134	12.487	4.554	11.631	5.816	10.608	6.873
2.6000	13.856		13.716	1.628	13.299	3.191	12.630	4.635	11.754	5.917	10.707	6.988
2.6200	14.031		13.887	1.658	13.459	3.250	12.774	4.718	11.876	6.018	10.806	7.102

FIG. 17. A part of a migration list sorted in order of time for each stepout.

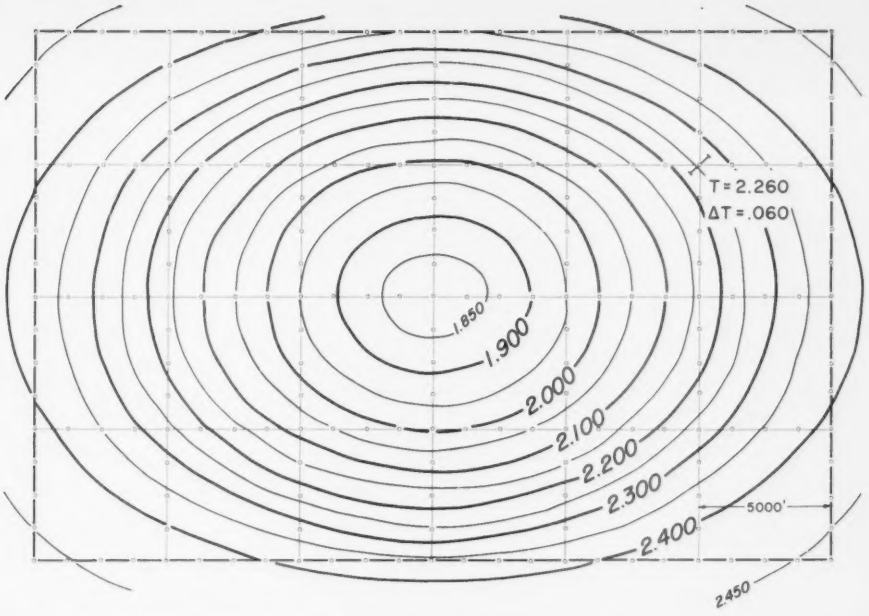

FIG. 18. A time map of an anticline showing the shotpoint grid with 5,000 ft between lines and 1,250 ft between shotpoints. An example time (T) and stepout (ΔT) are shown for which depth and offset information is obtained from the list shown in Figure 17.

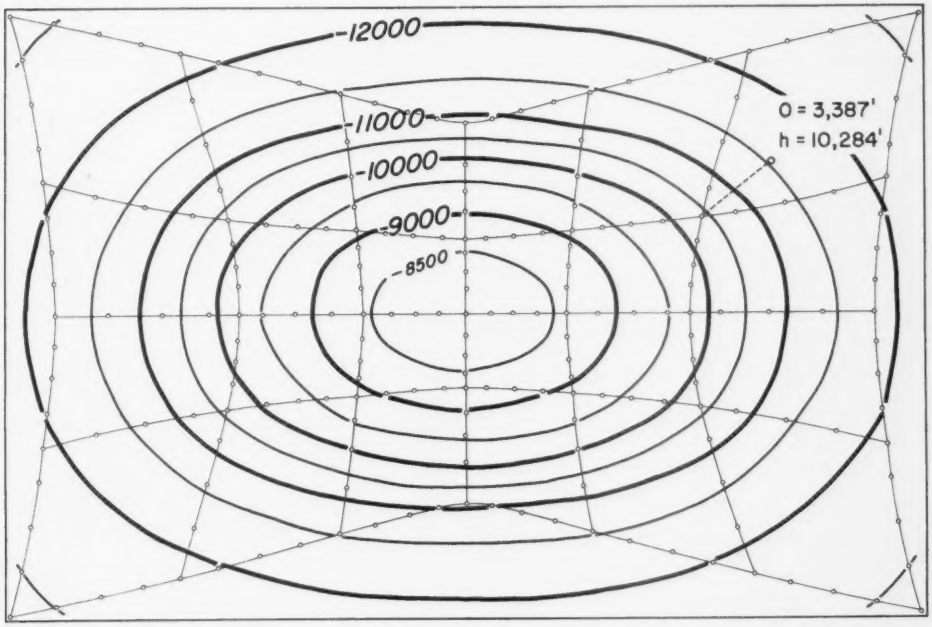

FIG. 19. A depth map made by three-dimensionally migrating the time map shown in Figure 18. The migrated location for each shotpoint is shown by the converging grid.

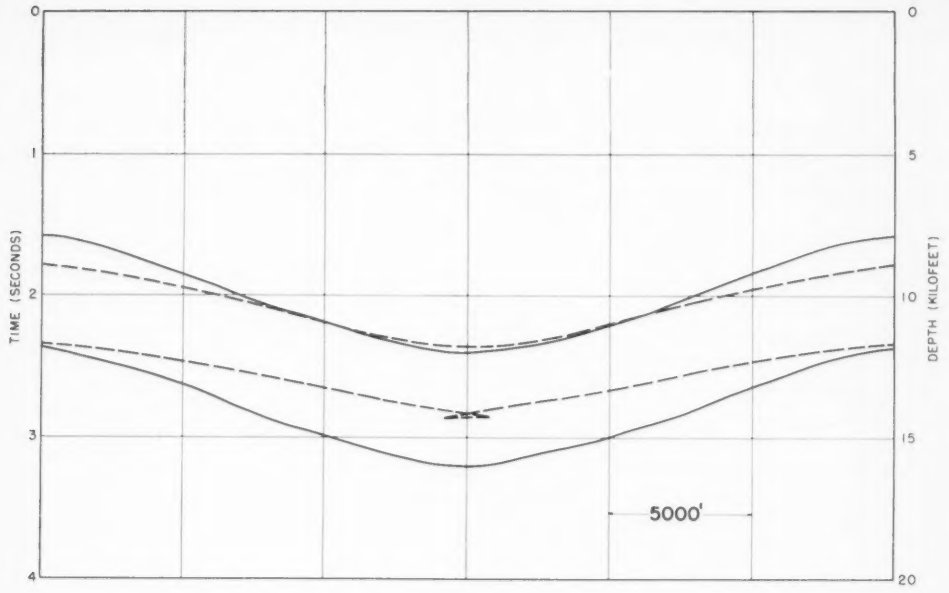

FIG. 20. An east-west cross-section across two synclines. They are referred to as a shallow and a deep syncline.

showing the migrated position of all the shotpoints. The displacement of the shotpoints is greatest in the area of steepest dip.

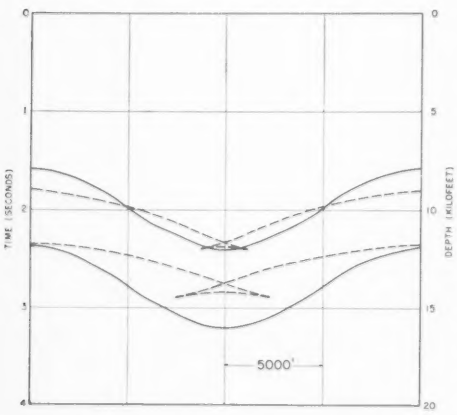

FIG. 21. A north-south cross-section of a shallow and a deep syncline. (Note the increasing effect of the buried focus crossing of the time limbs. The amount of cross-over on the time plots increases either with the narrowness of the syncline or the depth of the syncline.)

Figure 24 shows a time map of the deep syncline. The time overlap caused by the buried focus in the center gives a very complex picture. When all of these times are migrated and converted to depth, they give a very smooth syncline as shown in Figure 25.

FIELD METHOD OF THREE-DIMENSIONAL MIGRATION

The migration list made by the electronic computer can be used in any field office to migrate time maps simply and accurately. The procedure to follow is to make a time map as complete as possible. From the time map read values of travel time and ΔT. Lay off the offset on an overlay at right angles to the time contours. Post depths at the migrated points and contour the depth map. This process is simplified by making the time contours have the same values as calculated wave fronts on the list, then migrate only points on contours controlled by data. This elimination of interpolation is the secret of speed.

SUMMARY

The electronic computation of wave-front charts is an improvement over other methods

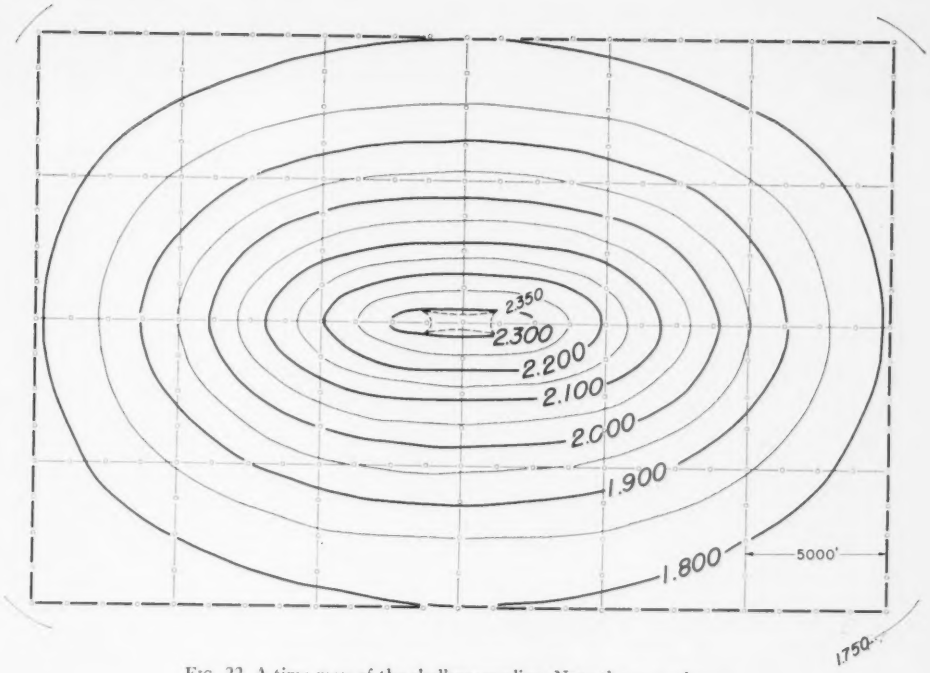

FIG. 22. A time map of the shallow syncline. Note the crossed over or hidden contour in the center (dashed).

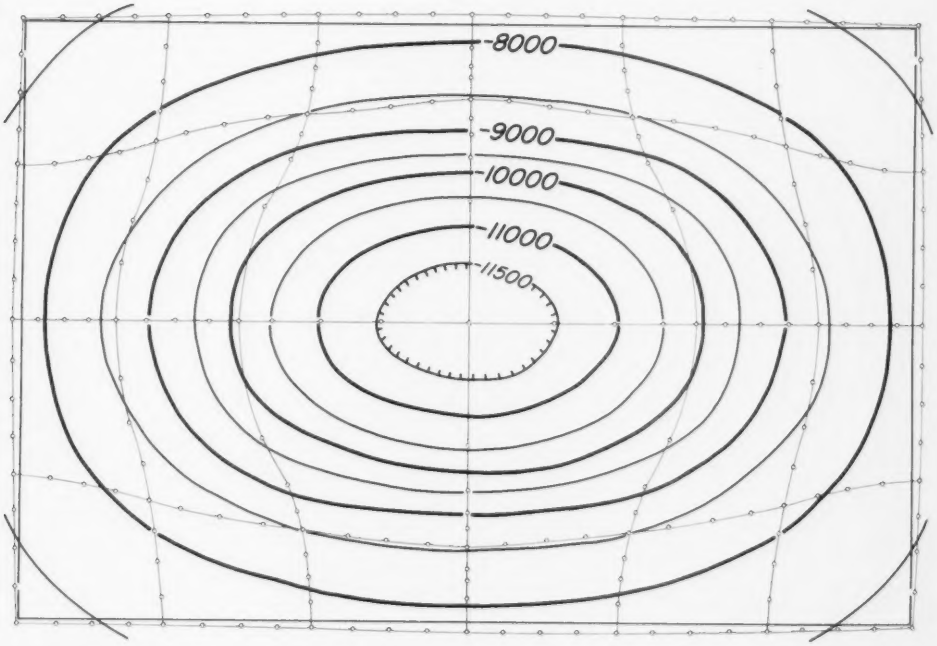

FIG. 23. A depth map of the shallow syncline showing the divergence of the shotpoint grid.

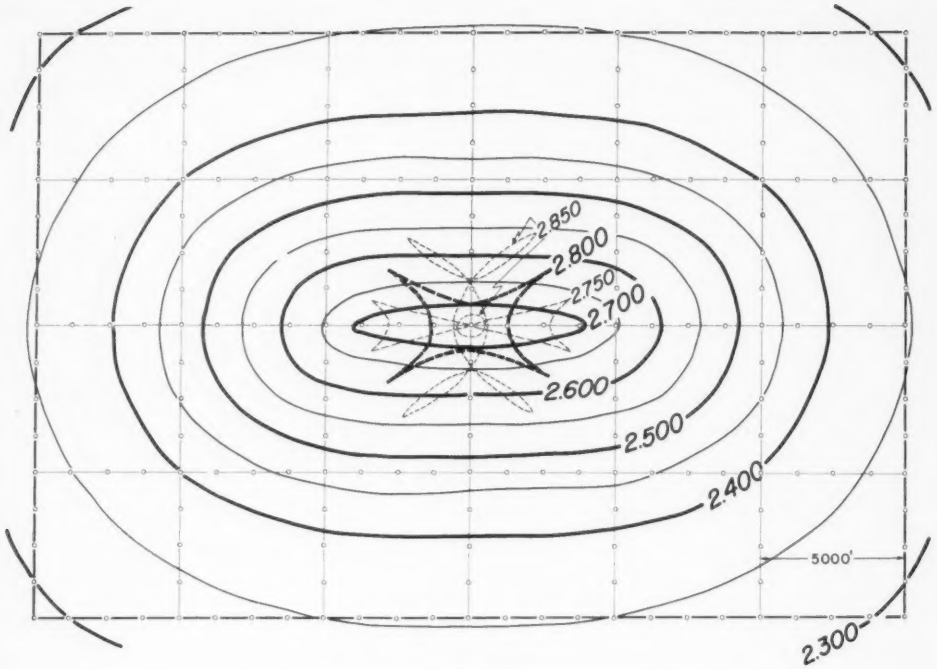

FIG. 24. A time map of a deep syncline. The crossed over or hidden contours are dashed.

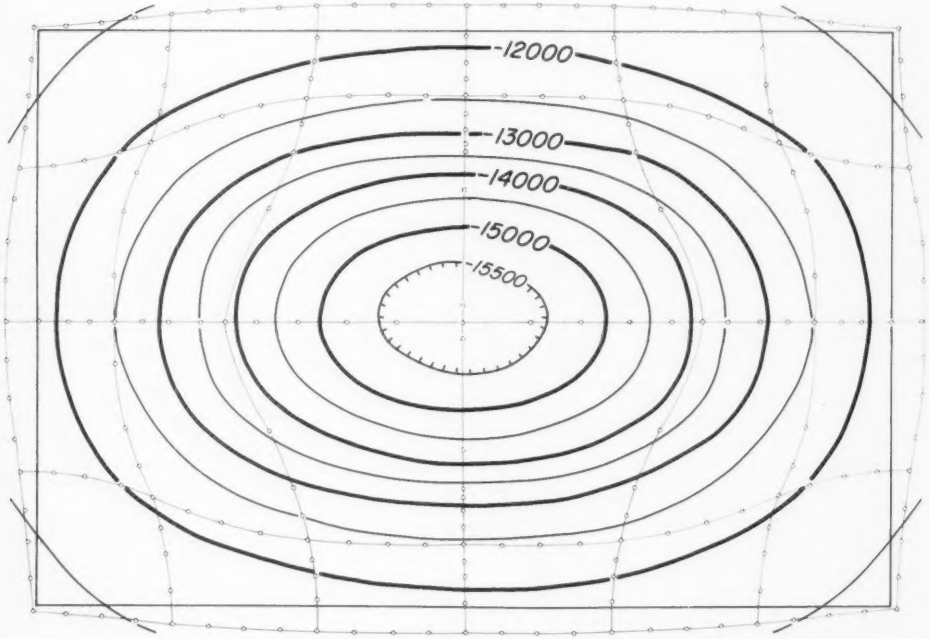

FIG. 25. A depth map of the deep syncline showing the divergence of the migrated shotpoint positions.

because: (1) Mathematical assumptions may be used that reduce the time required to determine the constants needed for calculation. (2) The speed of the computer reduces the time required to obtain a chart with increased accuracy. (3) The detailed calculations that can be handled by the machine program allow the use of complex, discontinuous velocity functions. Many layers may be included having almost exact correspondence to observed velocity data. (4) Trained personnel are not required to make the calculations after the program is completed and a check list of the input information is made. Personnel may need considerable review for manual calculations if charts are infrequently required, but the computer program retains its speed. (5) The migration lists allow easy and efficient migration in three dimensions. The lists may be made so detailed that no interpolation is necessary.

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AN APPROACH TO INVERSE FILTERING OF NEAR-SURFACE LAYER EFFECTS FROM SEISMIC RECORDS*

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This paper suggests a scheme for compensating the effects that the near-surface stratification, variable from spread to spread, produces on both the character and the timing of the seismic traces. For this purpose, accurate near-surface velocity information is mandatory. This scheme should greatly reduce the correlation difficulties so frequently encountered in many areas. It may also be used to enhance the resolving power of the seismic reflection technique. The approach presented here is based on the rather restrictive assumptions of normal incidence, parallel equispaced plant reflectors, and noiseless conditions.

INTRODUCTION

The interpreter of a seismogram obtained during an oil exploration survey is primarily concerned with structural or stratigraphic features of the subsurface. However, being necessarily restricted to operate near the surface, he is unable to receive the subsurface information without its being distorted by the screening effect of the near-surface conditions.

This screening effect is very complex, but it may be assumed to comprise primarily a delaying action and a distorting action. Both of these effects have been noted since the very beginning of seismic reflection prospecting, when the need for weathering correction and the role of the charge location were discovered and investigated.

In the less remote past, attention has been directed to the complications of records by the presence of ghosts due to reflections occurring at the surface or at the base of the weathering, to the problems of multiples, and to that of singing records so often observed in water-covered areas. Hence, there is no doubt that the importance of near-surface effects is well recognized by oil geophysicists who, most of the time, wish they could get rid of them.

The purpose of this article is to present a more generalized treatment of this type of problem and to suggest an approach to its solution. In addition, the need for accurate near-surface velocity information is stressed if the interpreter is to make a correct interpretation of the later portions of a seismogram. The basic philosophy underlying this approach is that:

(1) All the information concerning the deep stratification must of necessity pass through the shallow strata where it may be distorted before it is revealed on the seismic trace.

(2) Sharp velocity contrasts are common in the shallow stratification, and their magnitudes and separations vary more erratically there than those of the deeper section.

(3) In these conditions, we must conclude that interpretation and correlation difficulties may well be primarily due to the effects that changes in shallow stratification and source location from spread to spread have on the character as well as on the timing of the events appearing on the seismic trace.

Accordingly, the proposed approach consists of

(1) determining with maximum possible accuracy the velocity profile of the near surface, and

(2) from this knowledge and that of the location of the source, operating on the field trace in such a fashion as to transform it into a new trace which reflects only the effects of the deep stratification.

This approach may be viewed as a refinement of the old method for computing corrections. In the past, we were satisfied with merely shifting the traces relative to each other by applying time corrections. Now, in addition, we propose to manipulate the trace, by use of the independently predetermined near-surface conditions, to remove

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the major effects that these shallow variations have on the character of the trace.

Actually, the old correction method being a very crude first approximation of the new method, an approximation which has proven itself satisfactory on many occasions, a rather small refinement may well be all that is needed to extend substantially the domain of workability of the reflection technique.

In view of the assumed importance of the near-surface effects, whatever the approach followed in interpreting the trace, the chances for success depend largely upon the availability of accurate shallow velocity information. Such is rarely available with our present logging technique. This may be due to the fact that, in most cases, many considerations outside the domain of the exploration personnel (drilling, production, etc.) bear heavily on the development of the logging tools and procedures. However, since failure or success of costly exploration efforts may hinge around this shallow velocity information, we should raise our voices louder and make our most important needs clearer to the logging experts.

SUGGESTED APPROACH

The approach is based on the fact that, given a stratified system comprising n layers defined by $n+1$ interfaces spaced at equal travel time interval τ, the reflection response of the entire system can be expressed simply as a function of the reflection and transmission responses of two complementary portions of the system, as will be shown later.

However, before doing so, it is useful to state the very limiting assumptions on which the theory is built. It is generally recognized that the propagation of seismic waves in a stratified system as complex as the sedimentary portion of the earth can be investigated only at the cost of making almost unacceptable simplifying assumptions. However, some insight may be gained by the solution of such oversimplified problems. This is the case here. The problem treated is restricted to normal incidence, and the propagation characteristics of the medium are functions of only one space variable, that along which the waves propagate. For simplicity, we further assume constant density.

Within these assumptions, it may easily be shown (see Appendix) that the reflection and transmission responses, R_0^m and T_0^m, respectively, of a system of m layers having equal travel time τ, numbered from 1 to m and bounded by interfaces numbered from 0 (the surface of the system) to m, may be expressed by polynomials in $x=e^{-i\omega\tau}$ which are ratios of easily written polynomials in x. Similar expressions have been obtained previously in optics (Abeles, 1946; Crook, 1948), and we recommend these papers to the reader interested in more details.

The results obtained for the reflection response of the single-layer case (comprising two interfaces) can be used to suggest a general relation which would permit the separation of the effects of the shallow portion of a stratified system from those of the deep portion.

Since we are interested in splitting the complete system into two complementary portions, we are led to split the one-layer system into two complementary portions comprising, respectively, the upper and the lower interface.

In the single-layer case we find

$$R_0^1 = \frac{r_0 + r_1 x^2}{1 + r_0 r_1 x^2} . \tag{1}$$

In this formula the x^2 terms indicate the two-way travel time of the layer.

Formula (1) can be modified as follows:

$$R_0^1 = r_0 + \frac{(1 - r_0^2) r_1 x^2}{1 + r_0 r_1 x^2}$$

$$= r_0 + \frac{(1 + r_0)(1 - r_0) r_1 x^2}{1 + r_0 r_1 x^2} .$$

Noting that $(1+r_0)$ is the transmission coefficient, t_0, of the top layer in a downward direction, that $(1-r_0)$ is its transmission coefficient, $\bar{t}_0$, upward, and that the reflection coefficient, $\bar{r}_0$, of the interface to a wave impinging on it from below is equal to $-r_0$, we can write

$$R_0^1 = r_0 + \frac{t_0 \bar{t}_0 r_1 x^2}{1 - \bar{r}_0 r_1 x^2} . \tag{2}$$

This formula (2) is identical to (1), but it is much more closely related to the physical phenomenon.

Replacing single interfaces by systems of interfaces, we can write the general formula for a system of n layers including i layers in the shallow portion,

$$R_0^n = R_0^i + \frac{T_0^i T_i^0 R_i^n{}_{+1} x^2}{1 - R_i^0 R_i^n{}_{+1} x^2} , \tag{3}$$

which is easily verified on simple systems.

In this formula, R_0^n is the reflection response of the entire system; R_0^i is that of the top i layers (the shallow portion of the system) to a unit amplitude wave impinging on the upper interface (the surface); R_i^0 is that of these same layers to a unit amplitude wave impinging upward on the bottom interface; T_0^i is the transmission response of these same i layers to the source impulse as emerging downward at the base of the shallow portion; T_i^0 is the transmission response to a wave traversing these layers in an upward direction; and finally, R_{i+1}^n is the response of the deep portion of the system comprising all the layers below the $(i+1)$th interface. Note, in addition, that T_0^i and R_0^i can include the effect of the source location within the shallow portion of the system.

The interpretation of this formula in terms of physical significance is straightforward. Clearly, the responses of the shallow portion and that of the entire system are identical as long as the energy which has been transmitted through the shallow portion and reflected by the deep portion has not yet returned to the surface. Then, the second term of the right-hand member of the formula takes on its first value. The numerator of this second term expresses the effect of the two-way transmission through the shallow portion of the system on the energy reflected by the deep portion. The denominator takes care of the reintroduction into the deep portion of part of the energy impinging upwardly on the shallow portion.

Hence, if the velocity profile of the shallow portion has been accurately determined by an independent investigation, it is simple to derive the four responses, R_0^i, T_0^i, R_i^0, and T_i^0, to be used in the formula.

Since the ultimate goal is the determination of the response R_{i+1}^n, we rewrite formula (3) in the form,

$$R_{i+1}^n = \frac{(R_0^n - R_0^i)x^{-2}}{T_0^i T_i^0 + R_i^0(R_0^n - R_0^i)} . \quad (4)$$

R_{i+1}^n is equal to zero until the time $2i$ because of the equality between R_0^n and R_0^i during the time interval $(0, 2i)$.

In these formulae, the x-term represents the two-way travel time within the layer separating the lower interface of the shallow portion from the upper interface of the deep portion.[1]

All quantities in the right-hand member of formula (4) are known with the exception of R_0^n However, the field trace, T, is known, and it represents the result of the convolution of R_0^n with the elementary wavelet, P, characterizing the traveling disturbance. Thus, if we can gain information concerning P, we can retrieve R_0^n by operating on T. Rather than attempting to detect the shape of the original disturbance or to derive it from statistical consideration, as is often suggested, it seems more logical to use this procedure.

The early part, T_i, of T (up to time $2i$) is due only to the known response, R_0^i, of the shallow portion, and therefore, within this part, T_i is the result of the convolution of R_0^i with P. Both T_i and R_0^i being known, we can operate on T_i and derive P. By considering T_i as a vector, we can use R_0^i to construct a matrix (see Appendix) which characterizes the operator transforming P into T_i.

$$\{T_i\} = \{R_0^i\}\{P\} \quad (5)$$

Then, by inverting the matrix $\{R_0^i\}$, we derive the operator needed to transform T_i into P.

Consequently, we derive P from T_i using

$$\{P\} = \{R_0^i\}^{-1}\{T_i\} . \quad (6)$$

Knowing P, we return to the entire trace, T, and consider it as resulting from a transformation of R_0^n by an operator determined by P. Accordingly, we write

$$\{T\} = \{P\}\{R_0^n\} \quad (7)$$

where, this time, the values characterizing the elementary wavelet are used to construct the matrix $\{P\}$ (see Appendix) which determines the operator required to transform R_0^n into T.

Since, in reality, we have T and want to find R_0^n, we invert the matrix $\{P\}$ and derive

$$\{R_0^n\} = \{P\}^{-1}\{T\} . \quad (8)$$

This supplies the last unknown remaining in formula (4); and subsequently we may now derive R_{i+1}^n by performing the operations indicated in the formula, thus determining the reflection response of the deep portion of the stratigraphic section as it would appear if the shallower section had been

[1] In equation (4), the responses are responses in the time domain, whose interpretation is explained in the last paragraph of Section I of the Appendix.

magically peeled off prior to the seismic survey.

While the relations between the trace, the elementary wavelet, and the reflection response have been presented in matrix form because of its compactness, it is clear that they could as well have been given as sets of simultaneous equations or as products and ratios of polynomials.

The method reported here relates only to the condition where no noise exists. When noise is present, the method may be extended readily by means of standard methods applicable in the study of stochastic processes. However, this subject is too large itself to be included in this paper.

CONCLUSIONS

We conclude by stressing again the importance of near-surface velocity information, so rarely available with our present techniques, hoping that, when this information is properly used, the efficiency of the seismic method will be increased sufficiently to make it applicable to a new range of exploration problems.

This approach, being idealistically exact, is clearly a generalization of the various inverse filtering schemes suggested or described by several authors (Backus, 1959; Lindsey, 1960; Wuenschel, 1960). However, there is a noticeable difference. The response of the whole system is not linearly related to the responses of the shallow and deep portions; and, as a consequence, a linear filtering approach can only be at best an approximation. Expressing the same fact in physical terms, a linear scheme does not take into consideration all the energy paths involved in the interaction between the shallow and deep portions of the system. In addition to the superposition of the effect of the stratification of the upper portion of the system upon the energy transmitted first downward and then upward, there is also the additional effect of the reflection of the energy reflected by the deep portion and impinging upward on the shallow portion. This last fact makes this interaction a nonlinear operation.

APPENDIX

I. DERIVATION OF THE REFLECTION AND TRANSMISSION RESPONSE OF A SYSTEM

We assume known the relationship between the amplitudes of the reflected and transmitted waves at the two successive interfaces, limiting the kth layer having a one-way travel time, τ_k.

$$\begin{Bmatrix} T_k \\ R_k \end{Bmatrix} = \frac{1}{t_k} \begin{Bmatrix} e^{i\omega\tau_k} & r_k e^{i\omega\tau_k} \\ r_k e^{-i\omega\tau_k} & e^{-i\omega\tau_k} \end{Bmatrix} \begin{Bmatrix} T_{k+1} \\ R_{k+1} \end{Bmatrix} = \{M_k\} \begin{Bmatrix} T_{k+1} \\ R_{k+1} \end{Bmatrix}. \tag{9}$$

Then, for a system comprising m interfaces on the surface of which a unit amplitude wave is impinging, we write

$$\begin{Bmatrix} 1 \\ R_0^m \end{Bmatrix} = \{M_0\}\{M_1\} \cdots \{M_{m-1}\} \begin{Bmatrix} T_0^m \\ 0 \end{Bmatrix}. \tag{10}$$

In the case of a single interface, we have (assuming $\tau_0 = 0$)

$$\begin{Bmatrix} 1 \\ r_0 \end{Bmatrix} = \frac{1}{t_0} \begin{Bmatrix} 1 & r_0 \\ r_0 & 1 \end{Bmatrix} \begin{Bmatrix} t_0 \\ 0 \end{Bmatrix} = \begin{Bmatrix} \dfrac{1}{t_0} \cdot t_0 = 1 \\ \dfrac{1}{t_0} \cdot r_0 \cdot t_0 = r_0 \end{Bmatrix}, \tag{11}$$

where

$$r_0 = \frac{V_1 - V_0}{V_1 + V_0}, \qquad t_0 = \frac{2V_1}{V_1 + V_0} = 1 + r_0. \tag{12a, b}$$

In the case of two interfaces (one layer),

$$\begin{Bmatrix} 1 \\ R_0^1 \end{Bmatrix} = \frac{1}{t_0}\begin{Bmatrix} 1 & r_0 \\ r_0 & 1 \end{Bmatrix}\frac{1}{t_1}\begin{Bmatrix} e^{i\omega\tau_1} & r_1 e^{i\omega\tau_1} \\ r_1 e^{-i\omega\tau_1} & e^{-i\omega\tau_1} \end{Bmatrix}\begin{Bmatrix} T_0^1 \\ 0 \end{Bmatrix}$$

$$= \frac{1}{t_0 t_1}\begin{Bmatrix} e^{i\omega\tau_1} + r_0 r_1 e^{-i\omega\tau_1} & r_1 e^{i\omega\tau_1} + r_0 e^{-i\omega\tau_1} \\ r_0 e^{i\omega\tau_1} + r_1 e^{-i\omega\tau_1} & r_0 r_1 e^{i\omega\tau_1} + e^{-i\omega\tau_1} \end{Bmatrix}\begin{Bmatrix} T_0^1 \\ 0 \end{Bmatrix}$$

$$= \{M_0^1\}\begin{Bmatrix} T_0^1 \\ 0 \end{Bmatrix}. \tag{13}$$

Therefore,

$$T_0^1 = \frac{t_0 t_1 e^{-i\omega\tau_1}}{1 + r_0 r_1 e^{-2i\omega\tau_1}}, \tag{14}$$

$$R_0^1 = \frac{1}{t_0}\cdot\frac{1}{t_1}\cdot(r_0 e^{i\omega\tau_1} + r_1 e^{-i\omega\tau_1})\cdot T_0^1, \quad \text{and} \tag{15}$$

$$R_0^1 = \frac{r_0 + r_1 e^{-2i\omega\tau_1}}{1 + r_0 r_1 e^{-2i\omega\tau_1}}. \tag{16}$$

For three interfaces (two layers) we have

$$\begin{Bmatrix} 1 \\ R_0^2 \end{Bmatrix} = \{M_0^1\}\frac{1}{t_2}\begin{Bmatrix} e^{i\omega\tau_2} & r_2 e^{i\omega\tau_2} \\ r_2 e^{-i\omega\tau_2} & e^{-i\omega\tau_2} \end{Bmatrix}\begin{Bmatrix} T_0^2 \\ 0 \end{Bmatrix}. \tag{17}$$

Therefore,

$$\begin{Bmatrix} 1 \\ R_0^2 \end{Bmatrix} = \frac{1}{t_0 t_1 t_2}\begin{Bmatrix} A & C \\ B & D \end{Bmatrix}\begin{Bmatrix} T_0^2 \\ 0 \end{Bmatrix}, \tag{18}$$

where

$$A = e^{i\omega(\tau_1+\tau_2)} + r_0 r_1 e^{-i\omega(\tau_1-\tau_2)} + r_1 r_2 e^{i\omega(\tau_1-\tau_2)} + r_0 r_2 e^{-i\omega(\tau_1+\tau_2)}$$

$$B = r_0 e^{i\omega(\tau_1+\tau_2)} + r_1 e^{-i\omega(\tau_1-\tau_2)} + r_0 r_1 r_2 e^{i\omega(\tau_1-\tau_2)} + r_2 e^{-i\omega(\tau_1+\tau_2)}$$

$$C = r_2 e^{i\omega(\tau_1+\tau_2)} + r_0 r_1 r_2 e^{-i\omega(\tau_1-\tau_2)} + r_1 e^{i\omega(\tau_1-\tau_2)} + r_0 e^{-i\omega(\tau_1+\tau_2)}$$

$$D = r_0 r_2 e^{i\omega(\tau_1+\tau_2)} + r_1 r_2 e^{-i\omega(\tau_1-\tau_2)} + r_0 r_1 e^{i\omega(\tau_1-\tau_2)} + e^{-i\omega(\tau_1+\tau_2)}. \tag{19a, b, c, d}$$

Consequently,

$$T_0^2 = \frac{t_0 t_1 t_2}{e^{i\omega(\tau_1+\tau_2)} + r_0 r_1 e^{-i\omega(\tau_1-\tau_2)} + r_1 r_2 e^{i\omega(\tau_1-\tau_2)} + r_0 r_2 e^{-i\omega(\tau_1+\tau_2)}}$$

$$= \frac{t_0 t_1 t_2 e^{-i\omega(\tau_1+\tau_2)}}{1 + r_0 r_1 e^{-2i\omega\tau_1} + r_1 r_2 e^{-2i\omega\tau_2} + r_0 r_2 e^{-2i\omega(\tau_1+\tau_2)}}, \tag{20}$$

$$R_0^2 = \frac{T_0^2}{t_0 t_1 t_2}(r_0 e^{i\omega(\tau_1+\tau_2)} + r_1 e^{-i\omega(\tau_1-\tau_2)} + r_0 r_1 r_2 e^{i\omega(\tau_1-\tau_2)} + r_2 e^{-i\omega(\tau_1+\tau_2)}), \tag{21}$$

and

$$R_0^2 = \frac{r_0 + r_1 e^{-2i\omega\tau_1} + r_0 r_1 r_2 e^{-2i\omega\tau_2} + r_2 e^{-2i\omega(\tau_1+\tau_2)}}{1 + r_0 r_1 e^{-2i\omega\tau_1} + r_1 r_2 e^{-2i\omega\tau_2} + r_0 r_2 e^{-2i\omega(\tau_1+\tau_2)}}. \tag{22}$$

By induction, it is then easy to show that, for any number of interfaces, the transmission response will be expressed as

$$T_0^m = \frac{t_0 t_1 \cdots t_m \exp\left\{-i\omega \sum_0^m \tau_i\right\}}{1 + M + N + \cdots}, \tag{23}$$

where

$$M = \sum_{i=0}^{m-1} \prod_{0,1}^{m-1,m}{}_{i,j} \exp\left\{-2i\omega\left\{\sum_0^j \tau_j - \sum_0^i \tau_i\right\}\right\}, \tag{24}$$

$$N = \sum_{i=0}^{m-3} \prod_{0,1,2,3}^{m-3,m-2,m-1,m}{}_{i,j,k,l} \exp\left\{-2i\omega\left(\sum_0^l \tau_l - \sum_0^k \tau_k + \sum_0^j \tau_j - \sum_0^i \tau_i\right)\right\}, \tag{25}$$

. . . . . .

and

$$R_0^m = \frac{\sum_{i=0}^m r_i \exp\left\{-2i\omega \sum_0^m \tau_i\right\} + \sum_{i=0}^{m-2} \prod_{0,1,2}^{m-2,m-1,m}{}_{i,j,k} \exp\left\{-2i\omega\left(\sum_0^k \tau_k - \sum_0^j \tau_j + \sum_0^i \tau_i\right)\right\} + \cdots}{1 + M + N + \cdots}; \tag{26}$$

where $\Pi_{i,j}$ denotes the products $r_i r_j$, $\Pi_{i,j,k,l}$, $\cdots$ denotes the products $r_i r_j r_k r_l \cdots$, and so on, with $\cdots > l > k > j > i$ integers ranging from 0 to n, and where the general expression for the time summation is

$$\sum_{i,j,\cdots,p}' (\tau) = \sum_0^p \tau_p - \sum_0^\sigma \tau_\sigma + \cdots + \sum_0^j \tau_j - \sum_0^i \tau_i. \tag{27}$$

If all the τ's are equal, these summations are equal to a multiple of τ. Putting $e^{-i\omega\tau} = x$, we can write

$$T_0^m = \frac{P_0^m(x)}{E_0^m(x)} \tag{28}$$

and

$$R_0^m = \frac{O_0^m(x)}{E_0^m(x)}, \tag{29}$$

where

$$P_0^m(x) = t_0 t_1 \cdots t_m x^m. \tag{30}$$

$E_0^m(x)$ and $O_0^m(x)$ are polynomials in x derived in the manner just described.

By Fourier transformation of the polynomials representing the steady-state response, it is seen that the coefficients in their expansion represent the impulse response as a sequence of amplitudes whose times of occurrences are indicated by the corresponding values of the exponent.

II. MATRIX EXPRESSION OF THE CONVOLUTION OF THE RESPONSE WITH THE ELEMENTARY WAVELET

The amplitude, T_j, of any sample point of a seismic trace at time, j, is clearly related to the reflection response, and the elementary wavelet, P, sampled amplitudes by

$$T_j = R_{j-p}P_p + R_{j-q}P_q + \cdots + R_{j-s}P_s \tag{31}$$

where s may be equal to zero if the interval between R_{j-p} and R_{j-s} happens to be equal to the duration of the wavelet, $s - p = n$, where n is the number of sample points defining the wavelet.

Considering a sequence of T_j's, the resulting set of simultaneous equations may be written compactly in matrix form in two ways, depending

whether the trace is considered as resulting from a transformation of P into T characterized by a matrix $\{R\}$, or whether it is considered as resulting from a transformation of R into T characterized by a matrix $\{P\}$.

It should be noted that the number of equations which are usable is entirely dependent on the sampling rate and that, in order to have at least as many equations as unknowns, we must use a sampling rate at least double that corresponding to the minimum interval separating two consecutive R's different from 0.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 761–764, 2 FIGS.

THE INFORMATION CONTENT OF A RIEBER SONOGRAM*

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Shortly after F. Rieber originally proposed the seismic data processing method of controlled directional sensitivity (CDS), whose end-product is a "sonogram," considerable criticism and discussion of the method appeared in geophysical literature. Certain of this criticism apparently had to do with the belief that CDS did not faithfully preserve all the information contained in the original field recording. This paper shows by a simple argument based on Fourier Transforms that CDS causes no such loss of information.

INTRODUCTION

As early readers of GEOPHYSICS will recall, shortly after F. Rieber (1936) introduced reproducible seismic recording and proposed the then new seismic data-processing method of controlled directional sensitivity (CDS), certain criticisms of the method appeared in geophysical literature (Mott-Smith, 1937). The main theme of this criticism seemed to be that the CDS process entails an inevitable loss of much of the information originally residing in the conventional field seismogram. Although both Rieber (1937b) and C. H. Johnson (1937) replied to most of this criticism, one important point appears to have been overlooked; namely, that the CDS process ordinarily causes no loss of information whatsoever.

In the 24 years intervening since 1937, no demonstration of the information-preserving properties of CDS has appeared in published geophysical literature to the author's knowledge. In view of the fact that CDS has seen considerable use in recent years (Riabinkin, 1947, 1957; Riabinkin, et al, 1957) and in view of the fact that a number of processes related to CDS have been developed recently (Tullos and Cummings, 1961; Bortfeld et al, 1960; Seelis, 1960), it is appropriate that the question of information loss in CDS processing be examined at the present time.

THE FORMATION OF A SONOGRAM

For the benefit of those not intimately familiar with Rieber's CDS method, it is worthwhile to review briefly the essential principles of the process. Suppose we have the hypothetical conventional N-trace seismogram with the two idealized interfering events possessing moveouts, Δt_1 and $-\Delta t_2$, as shown in A of Figure 1. Although it is by no means essential to the arguments of this paper, we will simply for convenience assume that the seismogram has been statically and dynamically corrected so that the two events in question line up along essentially straight lines.

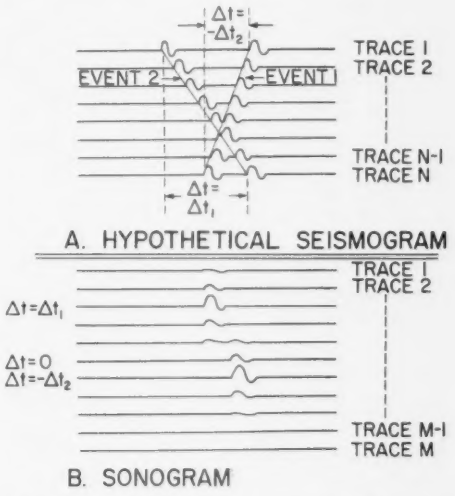

FIG. 1. The formation of a sonogram (B) from a seismogram (A). Seismogram event 1 appears on the sonogram trace marked $\Delta t = \Delta t_1$; event 2 appears on the sonogram trace marked $\Delta t = -\Delta t_2$.

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If we now imagine that the seismogram is recorded on an N-channel magnetic tape recorder provided with N movable, magnetic playback heads, then we can introduce arbitrary time shifts into the N seismic traces by means of these playback heads. In particular, we can align the heads with a moveout, Δt_1, and sum all the N traces together so as to enhance event 1 (and all other events with a moveout, Δt_1).[1] The sum trace resulting from this operation will be the trace marked $\Delta t = \Delta t_1$ in B of Figure 1. Similarly, if the heads are realigned with a moveout, $-\Delta t_2$, and if the N seismic traces are summed with this new set of time shifts, then event 2 will be enhanced and the trace marked $\Delta t = -\Delta t_2$ in B of Figure 1 will result. By continuing this procedure, we can seek events having other moveouts by simply aligning the playback heads for the desired moveout and summing the resulting time-shifted traces. In particular, if we do this M times with M different moveouts, we will produce the M-trace record shown in B of Figure 1. This latter presentation is the final product of the CDS method and has been referred to by Johnson (1938) as a "sonogram."

While it is not the purpose of this paper to discuss the art of picking sonograms or, for example, the extent to which interfering events can be resolved on a sonogram, these matters having been discussed by Rieber (1937a), Johnson (1938), and Riabinkin (1957); it is well to point out that the information sought from a sonogram is the same as that sought from a conventional seismogram; namely, the moveout, Δt, and the center-trace arrival time of each event. On a conventional record one does this by correlating an event across all the traces of a record. On a sonogram one can do this by finding that single trace on which the event develops its maximum amplitude. Furthermore, it would appear from the work of, for example, Riabinkin (loc. cit.) that the detection of other forms of information commonly sought by the geophysicist (character, so-called "fragmentary" events) can be more readily accomplished using sonograms than by using conventional seismograms. Finding, then, that practical experience seems to indicate no loss of information, it is of interest to see if this conclusion is theoretically sound.

[1] Rieber developed CDS prior to the advent of multichannel seismic tape recorders and used instead variable density photographic recording ("sound-on-film") as his reproducible recording medium. It is convenient, however, to describe his process in terms of present-day instrumentation.

THE INFORMATION CONTENT OF A SONOGRAM

As we have seen from the preceding discussion, the construction of a sonogram requires heavy mixing in that all traces of the conventional seismogram must be summed together. It might, therefore, appear at first glance that a considerable portion of the information originally residing in the N-trace seismogram is missing from the sonogram. Owing, however, to the fact that the mixing or summing process is carried out for M different sets of time shifts thereby producing an M-trace sonogram, it turns out, as we shall see, that no information is lost if M is at least as great as N.

The proof of this last statement is a straightforward matter and is accomplished by demonstrating that it is possible, given nothing but the sonogram and a knowledge of the processing parameters, to reconstruct exactly all N-traces of the original seismogram from the sonogram. If this is true, then a sonogram must obviously contain all the information originally present in the seismogram from which the sonogram was produced.

Referring to Figure 2, it is seen that in order to produce the mth sonogram trace corresponding to the moveout, Δt_m, it is necessary to introduce into the nth seismogram trace a time shift, Δt_n, where

$$\Delta t_n = (\Delta t_m/2)(N + 1 - 2n)/(N - 1). \quad (1)$$

For convenience, if we let $a = (N+1)/2(N-1)$ and $b = 1/(N-1)$, then equation (1) becomes

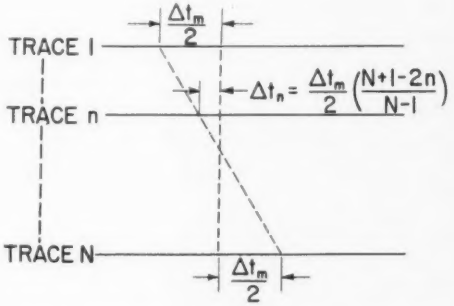

FIG. 2. Seismogram trace time shifts required for the production of a sonogram.

$$\Delta t_n = \Delta t_m(a - bn). \quad (2)$$

Observe that a and b depend only on the total number of traces, N, on the conventional seismogram and are independent of m and n.

If we designate the nth trace on the seismogram by $c_n[t]$, then, with time shifted for the mth sonogram trace, we will have the set of time-shifted traces,

$$c_n[t - \Delta t_m(a - bn)] \qquad n = 1, 2, 3, \cdots, N. \quad (3)$$

In order to produce the mth sonogram trace, $s_m[t]$, we simply sum the N traces represented by equation (3) to obtain

$$s_m[t] = \sum_{n=1}^{n=N} c_n[t - \Delta t_m(a - bn)], \qquad m = 1, 2, 3, \cdots, M. \quad (4)$$

For an M-trace sonogram there will be M such traces corresponding to the M different values of Δt_m.

Now let us Fourier Transform equations (4). If we let $S_m[\omega]$ be the transform of $s_m[t]$ and $C_n[\omega]$ be the transform of $c_n[t]$, then equations (4) become

$$\sum_{n=1}^{n=N} C_n[\omega] e^{-i\omega\Delta t_m(a-bn)} = S_m[\omega], \qquad m = 1, 2, 3, \cdots, M. \quad (5)$$

If Δt_m is assumed to be different in each of equations (5) (as will be true in practice) and if M is less than or equal to N, then equations (5) will constitute a set of M linear, independent, algebraic equations[2] for the N unknowns, $C_n[\omega]$, in terms of the known, $S_m[\omega]$, and the given processing parameters Δt_m, a, and b. If M is equal to N, a unique solution will thus exist for the $C_n[\omega]$. If M is greater than N, then $M-N$ of the equations will be derivable from the remaining N equations, so that the solution for $C_n[\omega]$ will still be unique. Consequently, given the values of a, b, and the sets, $s_m[t]$ and Δt_m; then, if M is greater than or equal to N, we can transform any N of the $s_m[t]$ into $S_m[\omega]$ and, from equations (5), find the unique solution for the N functions, $C_n[\omega]$. The $C_n[\omega]$ can then be inverted to obtain the desired $c_n[t]$. This set of functions, $c_n[t]$, will be identical to the $c_n[t]$ comprising the original seismogram from which the sonogram was derived. Since it is thus possible to reconstruct the seismogram exactly from the sonogram, all the information in the original seismogram must be fully preserved in the sonogram.

[2] Since $C_n[\omega]$, $S_m[\omega]$, and $e^{-i\omega\Delta t_m(a-bn)}$ are complex numbers, equations (5) actually represent $2M$ real equations in $2N$ real unknowns.

CONCLUSION

It has been demonstrated that the CDS process entails no loss of information provided the resultant sonogram contains at least as many independent traces as the original seismogram. This demonstration has been accomplished by showing that it is possible to recover each individual trace of the original seismogram directly from the sonogram itself.

The reader should not infer from the foregoing that the author is proposing a practical method of transforming a sonogram back into the original seismogram. Although the method will work in principle, the processing required in practice would be quite formidable. Even if the processing were straightforward, there is little point in performing such a transformation—the original seismogram is still available to us. The only point in demonstrating that the seismogram can be recovered from the sonogram is simply to show that no information is lost when a seismogram is transformed into a sonogram.[3] As a practical matter, some information will be lost owing to the inevitable introduction of noise by the instrumentation producing the sonogram. With properly designed instrumentation, however, this loss should be no more than that experienced with more conventional processing such as filtering and mixing. For all practical purposes, then, it can be assumed that no information loss occurs in CDS processing.

This conclusion in itself, of course, in no way shows that CDS and related processes possess any advantages over those of the more conventional seismic data-processing methods. Nonetheless, it would appear from the previously cited works of Rieber (1937a), Johnson (1938), Riabinkin et al

[3] It should be clear that the transformation of a seismogram into a sonogram is a much simpler process in practice than that of transforming a sonogram into a seismogram.

(1957), and Bortfeld et al (1960) that the CDS method may indeed have much to offer the exploration seismologist.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 765–771, 8 FIGS.

THE EFFECT OF SHOTPOINT MEDIUM ON SEISMIC COUPLING*

W. M. ADAMS† AND L. M. SWIFT‡

Two experiments on the coupling of seismic waves to the surrounding medium have been conducted. One was performed at two different overburden depths in a tunnel complex at the Nevada Test Site in the Oak Spring Tuff. The other was done at a depth of 800 ft in the Carey Salt Mine at the Winnfield Salt Dome near Winnfield, Louisiana. Free-field measurements within 400 ft of the chemical charges indicate that three to four times more energy was propagated into the elastic zone in the tuff than in the salt. There is some indication that in tuff the amount of energy transmitted into the elastic zone was dependent upon the lithostatic overburden pressure. Increasing the overburden pressure by a factor of about five almost quadrupled the energy propagated into the elastic zone.

INTRODUCTION

There is no adequate theory of the seismic phenomena associated with a completely contained explosive. In order to determine the effect of the medium about the shotpoint on the seismic coupling, an experiment is necessary. The purpose of this paper is to describe such an experiment.

EXPERIMENTAL ENVIRONMENT

Two media were studied: tuff at the Nevada Test Site, located 60 miles NNW of Las Vegas, and halite in the Carey Salt Mine near Winnfield, Louisiana. Only chemical explosives were used. For salt, the results of tamped shots conducted in an earlier "Project Cowboy" study, by Adams and Allen (1961), were used. For tuff, four shots were fired in under-reamed right-circular cylindrical holes at about 100 ft below the tunnel floor. See Figure 1. The shot program is given in Table I for the shots studied. Table II, data taken from Young (1961), states the physical properties determined for the tuff by two different methods.

Pelletol was used for the chemical explosive in both situations. It was presumably wet in the tuff, except for the 500-lb shot, and dry in the halite. Note that the lithostatic overburden was approximately the same for both media, about 1,000 psi, except for one 1,000-lb shot in tuff at an overburden of only 220 psi.

The ratio of the horizontal stress to the vertical stress was found to be about 1/2 for the tuff, by Merrill and Hooker (1960), and about 1 for the halite, by Merrill (1960). Other properties of the media are described by Guido and Warner (1960) and Warner and Violet (1959).

INSTRUMENTATION

The instrumentation was for radial particle velocity at three or more points in the elastic zone along a horizontal line at the depth of the shot as shown in Figure 1.

A pair of particle velocity traces recorded at

Table I. Shot program

Medium	Charge size (lb) Nominal	Charge size (lb) Actual	Overburden (ft)	Static stress (psi) measured *in situ** Vertical	Static stress (psi) measured *in situ** Horizontal
Tuff	100	103	1,055	1,120	730
	500	516	995	1,120	730
	1,000	967	1,010	1,120	730
	1,000	968	240	220	110
Halite	200	200	910	900	820
	200	200	910	900	820
	500	500	910	900	820
	1,000	1,003	910	900	820
	1,000	988	910		

* See Merrill and Hooker (1960) for measurements in tuff; in halite see Merrill (1960).

* This work was performed under the auspices of the U. S. Atomic Energy Commission. Manuscript received by the Editor March 16, 1961.

† Lawrence Radiation Laboratory.

‡ Stanford Research Institute.

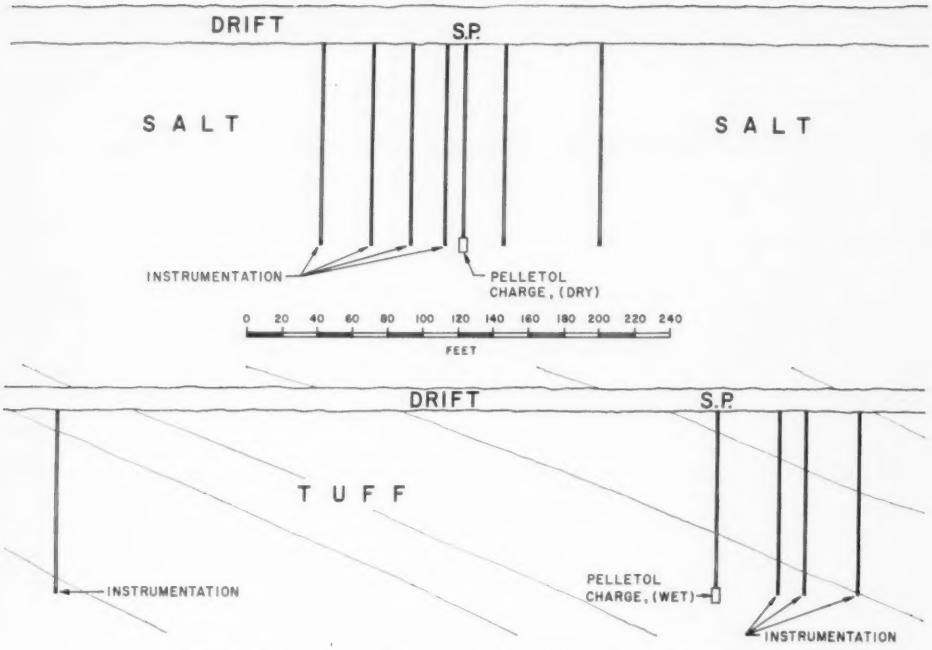

FIG. 1. Experimental environments of comparison tamped shots.

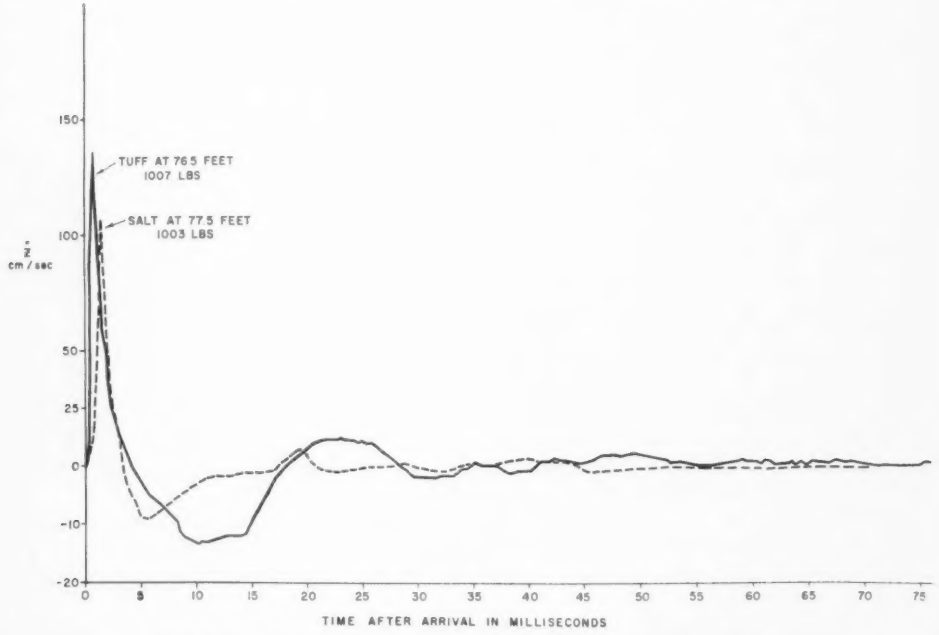

FIG. 2. Radial particle velocity at 80 ft from 1,000 pounds in tuff and salt.

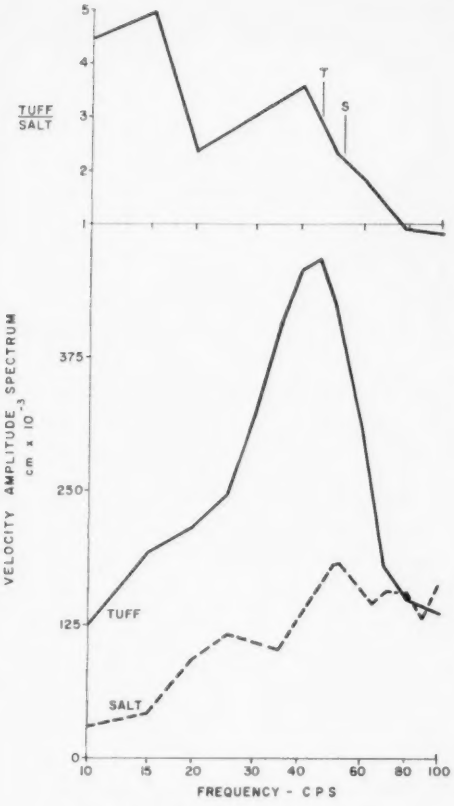

FIG. 3. Spectra and ratio of spectra for 1,000 pounds at 80 ft.

about 80 ft from 1,000 lb in each of the two media is given in Figure 2. For more original data, see Murphey (1961) and Swift (1961). Time and relative motion are designated on the figure.

For comparison of the medium effect, the velocity spectra of the particle velocity records were computed. Thus, if the trace be represented by $V(t)$, then we compute,

$$\hat{V}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} V(t) e^{-i\omega t} dt. \qquad (1)$$

These spectra are given in Figure 3 for the traces illustrated in Figure 2. Note that the dominant energy is in the frequency range of 30 to 60 cps. If we define the medium decoupling factor (D.F.) to be the ratio of these spectra as a function of frequency, we can form the appropriate ratio of the given curves to determine the medium effect on seismic wave generation:

$$\text{D.F.} = \frac{\hat{V}_{\text{tuff}}(\omega)}{\hat{V}_{\text{salt}}(\omega)}. \qquad (2)$$

This ratio is given in the upper portion of Figure 3. The average medium effect, tuff to halite, in the range of the dominant energy, appears to be more than two (significantly different from 1.3, the ratio of the recorded peak particle velocites as shown in Figure 2).[1] These data are for just one distance from one size of charge. To permit the synthesis of observations at different distances and for different charge sizes, the spectrum of the velocity potential reduced for sphericity was computed. This is explained as follows:

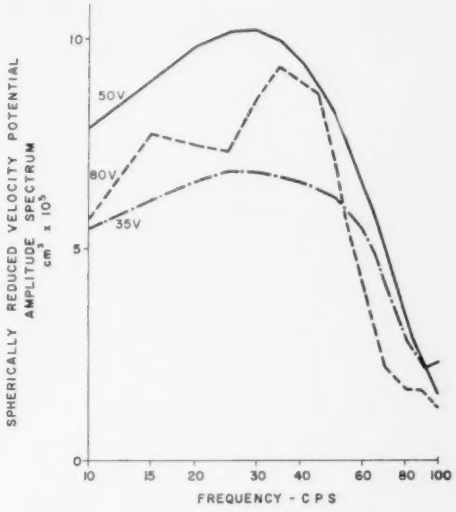

FIG. 4. Comparison of spherically reduced velocity potential at various distances, 35 ft, 50 ft, and 80 ft, for 1,000 lb. Hobo Shot No. 2 in tuff.

Define a spherical velocity potential by

$$V(r, t) = \frac{\partial}{\partial r}\left[\frac{\psi(t)}{r}\right] = -\frac{1}{r^2}\psi + \frac{1}{rc}\psi' \qquad (3)$$

where r is the radial distance, t is time, $c = r/t$ is the dilatational wave velocity, and the prime designates differentiation with respect to time.

[1] The ratio of recorded peak particle velocities is meaningful if the traces are identical in shape and differ only in amplitude.

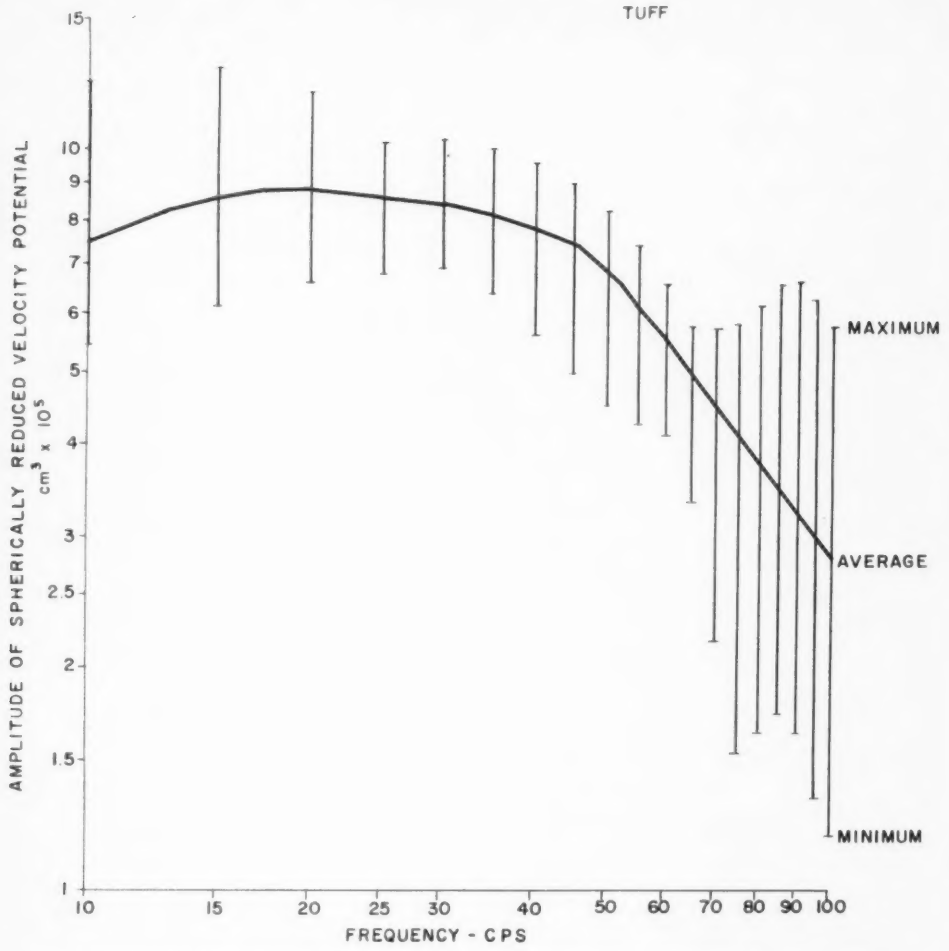

FIG. 5. Amplitude of spherically reduced velocity potential averaged over 6 traces from 3 shots (normalized to 1,000 pounds). All distances of observation were less than 100 ft.

Define $\hat{\psi}(\omega)$ and $\hat{\psi}'(\omega)$ as the Fourier transform of ψ and ψ', respectively, then

$$\hat{\psi}'(\omega) = i\omega\hat{\psi}(\omega). \tag{4}$$

Transforming (3) and using (4), we have

$$\hat{V}(\omega) = \left(\frac{i\omega}{rc} - \frac{1}{r^2}\right)\hat{\psi}(\omega). \tag{5}$$

The amplitude of the spherically reduced velocity potential, $\hat{\psi}(\omega)$, is given by

$$|\psi(\omega)| = \frac{r^2 c}{\sqrt{c^2 + r^2\omega^2}} |\hat{V}(\omega)|. \tag{6}$$

A few of the curves so calculated are shown in Figure 4. The numbers on the lines designate the approximate distance in feet from the shot. The potentials for the data obtained at distances greater than 100 ft were sometimes extremely irregular. As this might very likely be due to arrival of secondary wave types, no such observations were used in calculating the over-all aver-

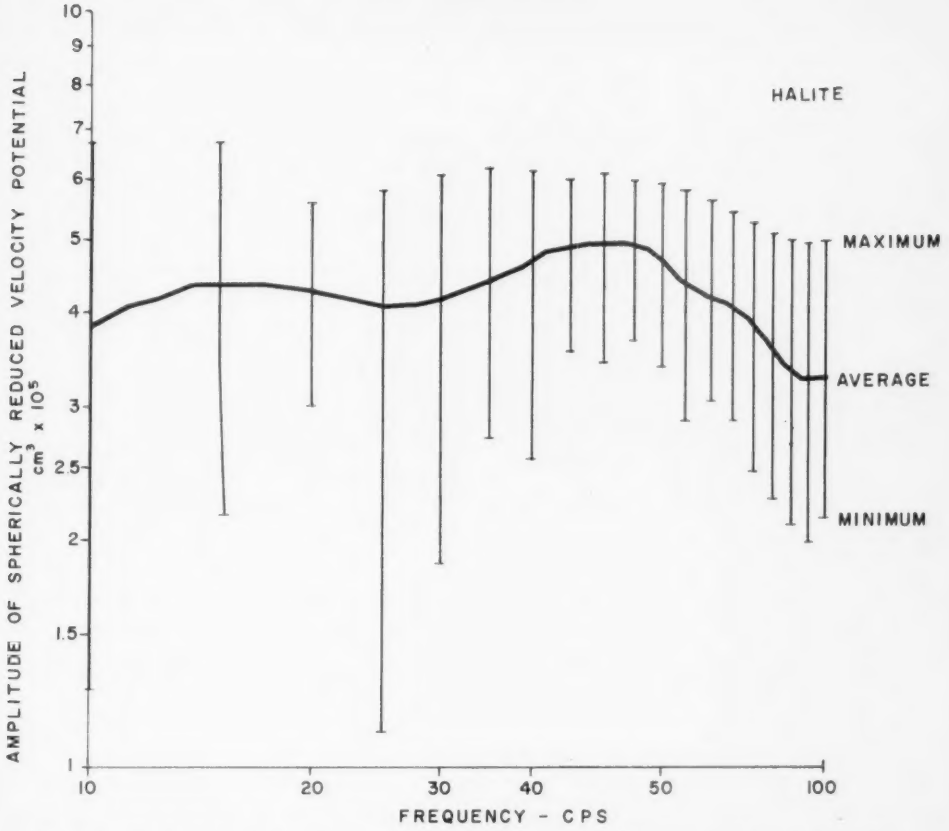

FIG. 6. Amplitude of spherically reduced velocity potential averaged over 9 traces from 5 shots (normalized to 1,000 pounds). All distances of observation were less than 100 ft.

ages for tuff and salt given in Figures 5 and 6. The maximum and minimum are also shown. If we define the medium coupling effect to be the ratio of the tuff velocity potential to the salt velocity potential, then the medium effect for the dominant range of frequencies 30 to 60 cps can be determined as shown in Figure 7. The standard deviation can also be estimated and is shown by the line lengths.

We conclude that seismic coupling for the frequency range considered is significantly different for tuff and halite, significant at the 95 percent level, and that the best estimate is a tuff-to-halite ratio of 1.6 ± 0.4.

A similar comparison of spectra for the spherically reduced velocity potential has been performed for the two 1,000-lb shots of Pelletol at two different overburdens in the same medium, tuff. Instrumentation was similar. The overburden depths were about 1,010 ft and 240 ft. Note that the ratio of depths is about four. Overburden pressures were measured and found to be about 1,120 and 220 psi, respectively. The ratio of overburden pressures is about five. The ratio of horizontal to vertical stress, k, was found to be about $1/2$ in both cases. The spectra for this comparison are given in Figure 8. The effect of varying the overburden by about four can be defined to be the ratio of the frequency components of the velocity potential for the range of dominant

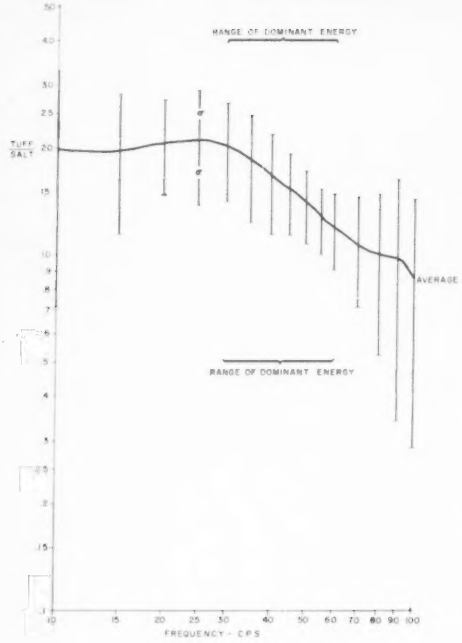

FIG. 7. Medium coupling for tuff to salt as a function of frequency.

energy, 30 to 60 cps. Carrying out these calculations, we find that the deeper shot, at 1,010 ft overburden, has components about 1.9 times those of the shallow shot at 240 ft overburden. The standard deviation is about 0.5. For the frequency range containing the dominant energy, 30 to 60 cps, the energy propagating into the elastic zone is almost quadrupled when the overburden pressure is increased by a factor of five.

Although there is some lithologic difference between the shotpoints, it is not considered significant; and the above results are considered valid.

ACKNOWLEDGMENTS

Roland F. Herbst suggested the use of the potential method in the data processing.

The data processing has been done by Thea Fefer and Florence Sullivan. Programming was accomplished by D. C. Allen and D. M. Brooks, both of whom contributed much to the completion of this work.

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Table II. Physical Parameters of Tuff at Two Depths by Two Methods (After Young)

Depth (feet)	Type	Density	Velocity (feet/sec)		Poisson's Ratio	Bulk Modulus ($\times 10^6$ lb/in^2)	Rigidity Modulus ($\times 10^6$ lb/in^2)	Young's Modulus ($\times 10^6$ lb/in^2)
			P	S				
240	Core	2.13	10,140	5,650	0.275	1.734	0.917	2.338
	In Situ		6,849	3,270	0.343	1.027	0.357	0.959
~1000	Core	1.84	8,580	4,250	0.377	1.232	0.449	1.204
	In Situ		7,990	3,837	0.346	1.084	0.370	0.996

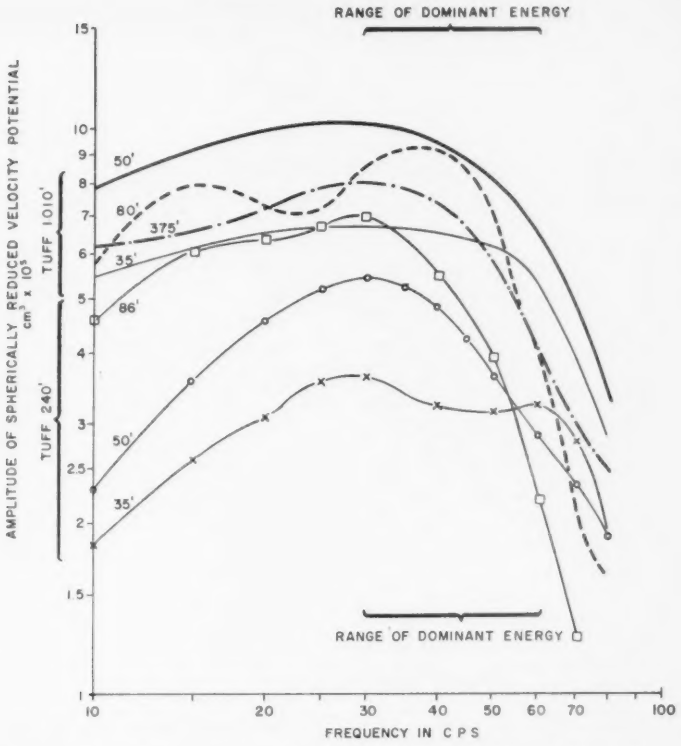

FIG. 8. Amplitude of transform of velocity potential reduced for sphericity. Tuff 1,010 ft to tuff 240 ft.

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GEOPHYSICS, VOL. XXVI, NO. 6 (DECEMBER, 1961), PP. 772-799, 33 FIGS.

SEISMIC DECOUPLING FOR EXPLOSIONS IN SPHERICAL UNDERGROUND CAVITIES*

WILLIAM M. ADAMS† AND DEWITT C. ALLEN†

A series of paired explosions in a salt mine near Winnfield, Louisiana, has been conducted to test a theory by A. L. Latter concerning seismic decoupling by underground cavities. The theory predicted a decoupling of 130. Free-field and surface measurements from an explosion in either a 6-ft- or a 15-ft-radius spherical cavity were compared with similar measurements from a completely tamped explosion of equal size. Shot sizes were from 20 pounds to a ton. Surface measurements were made out to 100 km. and covered the frequency range from 0.05 to 100 cps. The experiment confirmed that decoupling does occur. For explosions that produce an average cavity pressure up to one-fifth and possibly more of the lithostatic overburden pressure, seismic waves were decoupled by more than 100, i.e., two orders of magnitude. Even for explosions producing an average cavity pressure of six times the lithostatic overburden pressure, the seismic waves were decoupled by 20—more than a full order of magnitude. Minimum decoupling factors as a function of frequency are presented.

INDEX OF SYMBOLS

A area of sphere of radius a
a radius of spherical cavity
C dilatational velocity
c denotes close observation(<10 wave lengths) used only as subscript
D denotes decoupled, used only as subscript
d denotes distant observation (>10 wave lengths) used only as subscript
d_0 observed displacement at r_0
E energy
F decoupling factor, defined as the ratio of tamped to decoupled. It may be a function of frequency: $F(f)$.
f frequency, cycles per second
GZ ground zero
h denotes value for medium of hole shot
HE high explosive (chemical)
hf high frequency
I impulse
k bulk modulus
lf low frequency
LP long period
m mass
N noise
p pressure
p_0 constant pressure
r any arbitrary radius
r_0 radial distance of observation point
T denotes tamped, used only as subscript
t denotes value for medium of tamped shot, used only as subscript
U some component and aspect of the particle motion
V volume of sphere of radius a
W yield
γ ratio of specific heats
δ specific energy
λ Lamé modulus
μ shear modulus
π 3.1416
ω angular frequency
ω_0 C/a
Ω ω/ω_0
$\zeta(t)$ displacement versus time
$\widehat{\ }$ denotes Fourier transform
Λ denotes wave length
τ time lag

INTRODUCTION

A theory concerning the coupling of seismic energy to the medium was developed by Latter, LeLevier, Martinelli, and McMillan (1961). The

* This work was done under the auspices of the U. S. Atomic Energy Commission. It is a condensation of UCRL-6086. Manuscript received by the Editor March 4, 1961.

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idea, based on a theory for a shot in a large cavity and on an observation from a tamped nuclear shot, predicted that a notable reduction in the amount of seismic energy propagated from a tamped explosion could be achieved by shooting in a large cavity at depth in the earth. The decrease is because the free expansion of the shot within the cavity causes more energy to be retained locally as internal energy of the air in the cavity. For a tamped shot of the same yield, the hot gases do work on the surrounding medium which responds inelastically giving better energy transfer. The result is that the yield stress of the medium occurs at a much larger radius for the coupled shot than for the decoupled shot. The amount of decoupling is proportional to the square of the ratio of these radii.

Because of the relevance of these predictions to the Technical Conclusions of the 1958 Geneva Conference of Experts, an experiment was designed to test the theory. The moratorium on detonation of nuclear devices limited the explosions to chemical charges. A pair of shots, equal in yield, were detonated; one shot was well tamped, the other was in the center of a spherical underground chamber. Vibration measurements were obtained at a number of stations near the cavity and on the ground surface at distances up to 50 km. Comparison of these measurements from the two shots permitted a check on the validity of the theory. Several such pairs were fired, using two different cavities. This series of paired explosions is called Project Cowboy. One of the authors (W.M.A.) acted as advisor to the Technical Director, Dr. A. V. Shelton, for the surface measurement program and data analysis techniques, and participated in critical phases of the field execution including determination of initial gain settings and preliminary analysis and reporting. Both authors were responsible for the data reduction and interpretation described here and initially presented in part at the Triennial Meeting of the International Union of Geodesy and Geophysics in Helsinki, Finland.

The purpose of this paper is to present the results of an analysis of the surface seismograms recorded during Project Cowboy. The project and this analysis were conducted with the primary intent of providing experimental material for evaluation of a theory by Latter, et al (1961) concerning seismic decoupling in underground cavities. In particular, the data have not been studied for either determination of the geological structure of the experimental site or a determination of properties of the environmental media.

The only previous experiment on the decoupling of seismic energy by firing in an underground cavity is "Operation Orpheus," conducted by the United Kingdom Atomic Energy Authority and reported by Whiteside, et al (1960).

Theoretical Background

It has been shown theoretically that the ratio of the Fourier transform of a tamped shot to the Fourier transform of a shot in a spherical cavity is, for frequencies less than about 2 cps (equation 11 of Latter, et al, 1961),

$$\frac{\hat{\xi}(\omega)}{\hat{\xi}_h(\omega)} = \frac{16\pi}{3(\gamma - 1)} \frac{C_h}{C} \frac{\mu_h r_0^2 d_0}{W} . \qquad (1)$$

This ratio is defined to be the decoupling factor. Note that, as given, it is not frequency dependent.

When the hole is in the same medium as the tamped shot, $C = C_h$. The shear modulus has been determined (Nicholls, 1960) to be about 1.45×10^{11} g/cm sec^2 in the Winnfield Salt Dome. A velocity gage at a location corresponding to $r_0 = 1{,}098$ cm from 100 pounds of high explosive (2.1×10^{15} ergs) detonated in halite has been integrated to give a final displacement (Nuckolls) of 1.9×10^{-2} cm. Using these values, and $\gamma = 1.2$, we obtain a theoretical prediction for the seismic decoupling that is to be expected at distances of many wave lengths.

$$\text{Decoupling} = \frac{16\pi(1.45 \times 10^{11})(1098)^2(1.9 \times 10^{-2})}{3(1.2 - 1)(2.1 \times 10^{15})} \cong 130. \qquad (2)$$

There are several simplifications that have been made in obtaining the above result and these should be eliminated for the present circumstances. The principal difficulty is that the above value holds only for frequencies below about 2 cps. For the surface observations on Cowboy, all observed frequencies were higher than 2 cps. Therefore, two of the previous approximations are not permissible here. It is necessary to predict for frequencies up to 100 cps.

Oscillation of the Cavity.—The Fourier transform of the elastic displacement produced at a large distance r by a pressure step-function of

pressure p in a cavity of radius a is (equation 2 of Latter, et al, 1961, 1959)

$$\hat{\xi}_h(\omega) = \frac{pa}{8\pi\mu r} \frac{C}{\omega_0^2 + i\omega_0\omega - \frac{\lambda + 2\mu}{4\mu}\omega^2} . \quad (3)$$

For the case of low frequencies, only the ω_0^2 term in the denominator was considered. We now look at the higher order terms. We retain these terms and derive the decoupling as a function of frequency. For the cavity, from (3), letting $\omega/\omega_0 = \Omega$,

$$\hat{\xi}_h(\omega) = \frac{pa^3}{8\pi\mu_h r C_h} \frac{1}{\left(1 - \frac{\lambda + 2\mu}{4\mu}\Omega^2\right) + i\Omega} \quad (4)$$

so

$$|\hat{\xi}_h(\omega)| = \frac{pa^3}{8\pi r\mu_h C_h} \cdot \frac{1}{\left[\left(1 - \frac{\lambda + 2\mu}{4\mu}\Omega^2\right)^2 + \Omega^2\right]^{1/2}} ; \quad (5)$$

and, as before for the tamped shot (equation 10 of Latter, et al., 1961),

$$\hat{\xi}(\omega) = \frac{r_0^2 d_0}{2\pi r C} . \quad (6)$$

Hence for the same distance of observation for both shots,

$$\frac{\hat{\xi}_T(\omega)}{\hat{\xi}_h(\omega)} = \frac{16\pi r_0^2 d_0}{3(\gamma - 1)W} \mu \cdot \left\{1 - \left[2\left(\frac{\lambda + 2\mu}{4\mu}\right) - 1\right]\Omega^2 + \left(\frac{\lambda + 2\mu}{4\mu}\right)^2 \Omega^4\right\}^{1/2} . \quad (7)$$

To estimate the importance of the term in parentheses, let $\lambda = \mu$, so

$$\frac{\hat{\xi}_T(\omega)}{\hat{\xi}_h(\omega)} = \frac{16\pi r_0^2 d_0}{3(\gamma - 1)W} \mu \cdot \left(1 - \frac{\Omega^2}{2} + \frac{9}{16}\Omega^4\right)^{1/2} . \quad (8)$$

The term in parentheses is given versus Ω in Table I.

For a cavity having $a = 15$ ft, $C = 14{,}500$ ft (Nicholls, 1960), $\omega_0 = 968$, a frequency of 100 cps corresponds to $\Omega = 628/968 = 0.65$. The effects of neglected higher-order terms never exceed 12 percent.

Table I. Relative Effect of Higher-Order Terms in Fourier Transform of Shot in Cavity

$\Omega = \frac{\omega}{\omega_0}$	$\left(1 - \frac{\Omega^2}{2} + \frac{9}{16}\Omega^4\right)$
0	1.000
0.1	0.955
0.2	0.902
0.3	0.900
0.4	0.887
0.5	0.890
0.6	0.900
0.7	0.925
0.8	0.960
0.9	0.995
1.0	1.065

Effect of the Spike.—In deriving the earlier approximations we assumed that the pressure pulse impinging on the wall of the cavity was a step-function. In the case of a chemical explosive source this is a particularly poor approximation as there is a notable spike. For a better approximation let the pressure history be an impulse superimposed on a step-function. Then (Herbst)

$$\hat{p} = \hat{p}_0 + \hat{I} = \frac{p_0}{i\omega} + \frac{I}{A} , \quad (9)$$

where p_0 is a constant pressure, I is the constant corresponding to the Fourier transform of the impulse, and A is the surface area of the spherical cavity.

Assume that the impulse is entirely due to the H.E. hitting the wall of the cavity, so

$$I^2 = 2mE, \quad (10)$$

where m = mass of H.E. and E = energy release of H.E. Then

$$\frac{p_0}{i\omega} + \left(\frac{2mE}{A^2}\right)^{1/2}$$

$$= \frac{\hat{p}_0}{i\omega}\left[1 + i(2mE)^{1/2}\left(\frac{\omega}{p_0 A}\right)\right]. \qquad (11)$$

Taking absolute values,

$$|\hat{p}| = \left(\frac{\hat{p}_0}{\omega}\right)\left[1 + \frac{2mE\omega^2}{p_0^2 A^2}\right]^{1/2}. \qquad (12)$$

This effect is notable for the observed frequency range. The predicted relative effect versus frequency is as shown in Figure 1.

To obtain a more accurate prediction of the decoupling factor expected from observations at many wave lengths for the frequency range of 0.5 to 100 cps, it would be possible to obtain the Fourier transform of an observation of pressure in the near elastic region for the tamped shot and of the cavity pressure for the decoupled shot. Theoretically, the ratio of these should give the decoupling at distance.

Let the near-in displacement of the tamped shot and of the decoupled shot be $U_T(t)$ and $U_D(t)$, respectively. To obtain the motion at some distant point r, the source function is convolved with the impulse response function $R(t)$ of the particular raypath involved. Thus,

$$U_T(t)\,|_r = \int U_T(t)R(t-\tau)d\tau \qquad (13)$$

and

$$U_D(t)\,|_r = \int U_D(t)R(t-\tau)d\tau. \qquad (14)$$

Now for purposes of determining the decoupling factor, $F(\omega)$, defined as

$$F(\omega) = \frac{\hat{U}_T(\omega)}{\hat{U}_D(\omega)}, \qquad (15)$$

one would desire that

$$\frac{\hat{U}_T(\omega)\,|_r}{\hat{U}_D(\omega)\,|_r} = \frac{\int\left[\int U_T(t)R(t-\tau)d\tau\right]e^{-i\omega t}dt}{\int\left[\int U_D(t)R(t-\tau)d\tau\right]e^{-i\omega t}dt}$$

$$\stackrel{?}{=} \frac{\int U_T(t)e^{-i\omega t}dt}{\int U_D(t)e^{-i\omega t}dt} = \frac{\hat{U}_T(\omega)}{\hat{U}_D(\omega)}. \qquad (16)$$

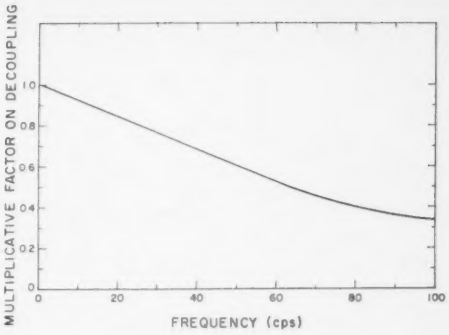

FIG. 1. Relative effect of pressure spike on decoupling factor.

Theoretically, this equality does hold. However, it appears to be sensitive to separation of paired shotpoints of less than one wave length (Herbst, et al, 1961). Hence, further refinement of the predicted decoupling will not be attempted here.

For comparison with the observed data to evaluate the theory of seismic decoupling, we will use the decoupling factor as modified for the effect of the spike. Although the findings presented here are derived for displacement, the decoupling factor determined is also valid for velocity and acceleration because all expressions involve Fourier transforms.

Experimental Design

As the theory of seismic decoupling is specifically developed for observations at large distances, it was necessary to give special consideration to the procedures employed in surface seismic recording. As many parameters as possible were kept constant between the tamped shot and the decoupled shot.

(a) The shotpoints were located as close together as feasible. As the salt medium about the two shot sites is considered homogeneous for about a kilometer in any horizontal or downward direction, the effect of not using exactly the same shotpoint is not considered serious. The average dominant frequency observed at distance was about 35 cps. In the salt, having a dilatational velocity of about 14,500 fps, the corresponding wave length is 415 ft. Horizontal separation of the shotpoints was about 400 ft, less than one wave length.

Assuming the salt dome to be no worse than transversely anisotropic, then the only effects on

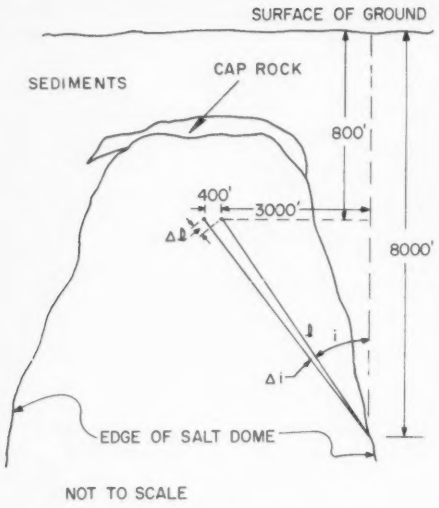

FIG. 2. Effects of separation of shotpoints.

the waves observed at a distance, predominantly head waves, were a slight variation in the angle at which the wave entered the particular formation from the salt dome and a very small change in the length of path in the salt dome. Using a formation at an 8,000-ft depth, estimates of these effects can be computed (see Figure 2):

$$\Delta i = \tan^{-1}\left(\frac{3400}{7200}\right) - \tan^{-1}\left(\frac{3000}{7200}\right)$$

$$= 2.7°, \text{ and} \qquad (17)$$

$$\Delta l = \left[(3400)^2 + (7200)^2\right]^{1/2} - \left[(3000)^2 + (7200)^2\right]^{1/2}$$

$$= 150 \text{ ft.} \qquad (18)$$

This distance is about one-third of a wave length of the dominant frequency observed at the distant stations.

(b) The variation due to drift in seismometers and recording apparatus was reduced by shooting the pair of shots no more than one hour apart.

(c) The variation due to variable coupling of a seismometer to the ground (O'Brien, 1957) was made negligible by the one-hour separation in time of the two events being compared.

(d) To minimize loss of usable recordings due to temporary increase in microseismic background, such as from trains, the array traces were visually monitored. This proved extremely important with the lower yields.

(e) To improve the signal-to-noise ratio of the surface seismograms, it was necessary to determine times of minimum microseismic activity. A strong correlation of the microseismic activity in the frequency range of 0.5 to 100 cps with weather conditions was observed, inclement weather increasing the amplitude. In particular, a strong diurnal variation by a factor of 2 or more was observed. The minimum occurred during the early hours of the morning. Therefore, in all but 3 of the 17 shots the shot times were restricted to between midnight and 4 a.m., local time (see Summary of Shot Data, Table II). This also corresponded with minimum cultural noise sources.

The primary feature of the seismograms is the amplitudes, not the times. Therefore, location of the stations was geometrical along a radial line. No seismic exploration shots without automatic gain control (AGC) had been made in the area, so prediction of the limits of location for the stations was difficult.

Test Site Environment

The pertinent shot data for the 17 shots comprising Project Cowboy are summarized in Table II. Note that comparable shots were fired as a pair, with even numbers being decoupled shots, odd numbers being tamped shots (except for 3, 4, 5, and 16). The depth below the surface of the earth was about 800 ft for the decoupled shots and about 900 ft for the tamped shots. The shotpoints were in the Carey Salt Mine near the central portion of a salt dome located near Winnfield, Louisiana. See Figure 3 for location.

The stratigraphy of the surrounding formations was supplied by the National Geophysical Company (Fraser) as derived from wells lying approximately along the radial line running WSW from the salt dome (see Figure 3). This is the direction which was instrumented on the surface out to 100 km.

The formations in the region strike NE-SW and dip about 5 degrees to the SE.

The geology of the Winnfield Salt Dome has been studied by Huner (1939), Cameron (1949), and Spooner (1926, p. 217–292, esp. p. 276–282). The diameter is about one mile with a step in the cap rock. The cap rock is composed of three zones; calcite, gypsum, and anhydrite. The thickness varies from 60 to 500 ft.

Table II. Summary of Shot Data—Project Cowboy
(December 1959–March 1960)

Shot No.	Date	Time (CST)	Yield (lb)	Station	Type
1	17 Dec.	0015	20	1.2	Coupled. 45-ft hole
2	17 Dec.	0045	20	1.1	Decoupled. 12-ft-diam. sphere
3	19 Dec.	0000	100	1.1	Decoupled. 12-ft-diam. sphere
4	19 Dec.	0015	100	1.3	Coupled. 45-ft hole
5	23 Jan.	0000:00.113	198.35	2.1	Decoupled. 30-ft-diam. sphere
6	30 Jan.	0001:00.112	200.0	2.1	Decoupled. 30-ft-diam. sphere
7	30 Jan.	0101:00.112	199.65	2.2	Coupled. 110-ft hole
8	6 Feb.	0001:00.115	477.4	2.1	Decoupled. 30-ft-diam. sphere
9	6 Feb.	0101:00.113	499.7	2.3	Coupled. 110-ft hole
10	13 Feb.	1901:00.113	954.0	2.1	Decoupled. 30-ft-diam. sphere
11	13 Feb.	2001:00.114	1003.0	2.4	Coupled. 110-ft hole
12	20 Feb.	0001:00.112	929.0	1.1	Decoupled. 12-ft-diam. sphere
13	20 Feb.	0100:59.614	987.6	2.5	Coupled. 110-ft hole
14	27 Feb.	0001:00.127	1902.4	1.1	Decoupled. 12-ft-diam. sphere
15	28 Feb.	0401:00.131	936.2	2.6	Coupled. 110-ft hole
16	3 Mar.	2301:00.128	199.5	1.4	Coupled. 45-ft hole
17	4 Mar.	0001:00.130	199.8	1.3–1	Coupled. 45 ft hole

Notes: (1) All times for Shots 5 through 17 are derived from comparisons with WWV. Accuracies are ±0.001 sec, except for Shot 15, which is ±0.003 sec.
(2) All yields include "Nitramon" booster and detonator weights of either 2 or 3 lb.
(3) For this paper, yield means pounds of Pelletol for chemical explosives, or kilotons of TNT equivalent in energy for nuclear explosives. One kiloton is 4.19×10^{19} ergs.

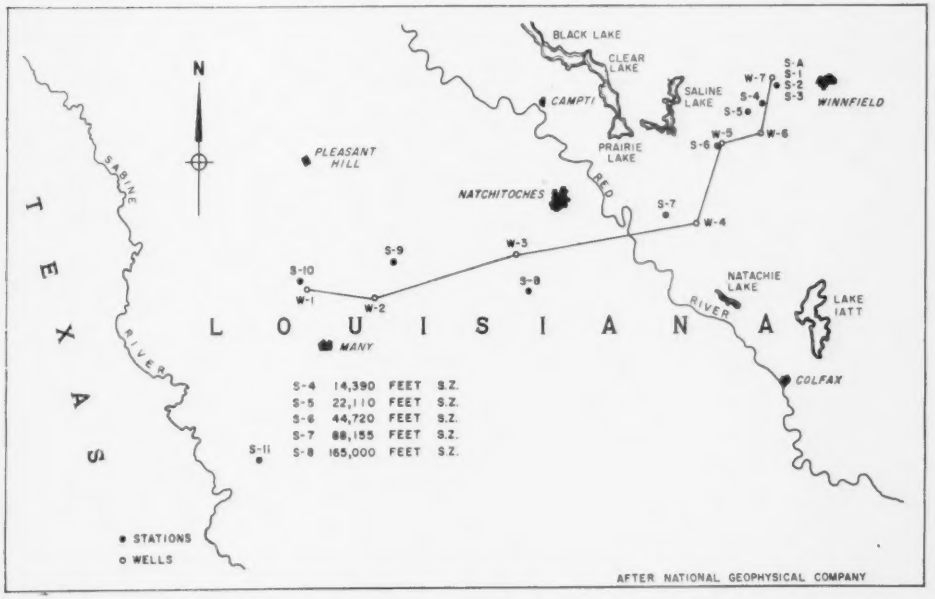

FIG. 3. Map of Winnfield Salt Dome and environs showing location of surface seismic stations (S-1, S-2, S-3, etc.) and wells (W-1, W-2, W-3, etc.) with respect to surface zero (S.Z.).

The salt is composed of alternate light and dark bands, varying in thickness from an inch to more than six inches. Hoy and O'Neill (1960) have mapped the structure of the salt exposed in the mine near the Cowboy working area.

The occurrence of carbon dioxide gas in noticeable amounts in the southwestern lobe of the dome prompted the selection of a site in the northeast lobe. Results were not affected by the explosive release of any gas pockets.

The Cowboy portion of the mine workings and the two spherical cavities are shown in Figure 4. Numbered locations are the shotpoints. Data from underground instrumentation with interpretation and analysis are presented in other reports (Murphey, 1961; Nuckolls, 1961).

Pertinent features to note are the relatively small separation of the tamped and decoupled sites. Also note from Table II that three tamped 1,000-lb shots (Shots 11, 13, and 15) were fired, permitting some experimental consideration of the effect of separation of shotpoints. Shots 16 and 17 were performed specifically for this purpose.

INSTRUMENTATION AND SEISMOGRAM DATA

The type of instrumentation used at each station for each shot is listed in Table III, a chart of surface instrumentation for this project. The

Table III. Instrumentation for Each Surface Seismic Station

Code: X = Analyzable signal; D = Signal only detectable; N = No signal; R = No record; I = Inoperable; Blank = Not fielded (or no record available); T = No timing lines

Station Distance (ft) to Surface Zero	Instrumentation	Shot Number															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Surface Zero	Accelerometers	N	N	N	X	N	N	X	N	X	N	X	N	X	X	X		
	Displacement meters	N	N	N	X	N	N	X	N	X	N	X	N	X	X	X		
	Experimental displacement meters	N	N	N	N	N	N	D	N	X	N	X	N	X	X	X	X	X
	One-second Benioff	X	N	X	X	I	N	X	N	X	X	X	N	X	X	X	X	X
	Twelve-element high-frequency	X	X	X	X													
2 772	Accelerometers	N	N	N	N	N	N	X	N	X	N	X	N	X	D	X	X	X
	Displacement meters	N	N	N	N	N	N	N	N	X	N	X	X	X	X	X	X	X
	Experimental displacement meters	N	N	N	N													
3 1,546	Accelerometers	N	N	N	N	N	N	D	N	N	N	N	N	N	N	N		
	Displacement meters	N	N	N	N	N	N	N	N	X	N	X	N	X	X	X		
	Experimental displacement meters	N	N	N	N	N	N	X	N	X	N	X	X	X		X		
A 5,030	Twelve-element array	X	N	X	X													
	Six-element low-frequency array																X	X
	Six-element high-frequency array																X	X
	Three-component low-frequency array																X	R
4 14,390	Six-element low-frequency array					D	X	X	X	X	X	X	X	X	X	X	T	X
	Six-element high-frequency array					D	X	X	X	X	X	X	X	X	X	X	T	X
	Benioff seismometers			N	X	N	N	X	N	X	N	X	X	X	X	X	X	X
	Three-component low-frequency					D	X	X	X	X	X	X	X	X	X	X	X	X
	Twelve-element array			N	X													
5 22,110	Six-element low-frequency array					D	D	X	X	X	X	X	X	X	X	X	X	X
	Six-element high-frequency array					D	D	X	X	X	X	X	X	X	X	X	X	X
	Benioff seismometers					N	N	X	N	X	N	X	N	X	D	X	X	X
	Three-component low-frequency					D	D	X	X	X	X	X	X	X	X	X	X	X
	Press-Ewing seismometers					N	N	N	N	N	N	N	N	N	N	N		
6 44,720	Six-element low-frequency array					N	N	X	N	X	N	X	X	X	X	X		
	Six-element high-frequency array					N	N	X	N	X	N	X	X	X	X	X		
	Benioff seismometers					N	N	X	N	X	N	X	N	X	N	X		
	Three-component low-frequency					N	N	X	N	X	N	X	X	X	X	X		
7 88,155	Six-element low-frequency array					N	N	N	N	X	N	X	N	X	N	X		
	Six-element high-frequency array					N	N	N	N	N	N	X	N?	X	N	X		
	Benioff seismometers					N	N	N	N	X	N	N	N	N	N	N		
	Three-component low-frequency					N	N	N	N	X	N	X	N	X	N	X		
8 165,000	Six-element low-frequency array					N	N	N	N	N	N	D	N	N	N	D		
	Six-element high-frequency array					N	N	N	N	N	N	N	N	N	N	N		
	Benioff seismometers					N	N	N	N	N	N	N	N	N	N	N		
	Three-component low-frequency					N	N	N	N	N	N	N	N	N	N	N		
9 221,390	Benioff seismometers					N	N	N	N	N	N	N	N	N	N	N		
10 270,463	Benioff seismometers					N	N	N	N	N	N	N	N	N	N	N		
11 323,830	Benioff seismometers					N	N	N	N	N	N	N	N	N	N	N		
	Press-Ewing seismometers					N	N	N	N	N	N	N	N	N	N	N		

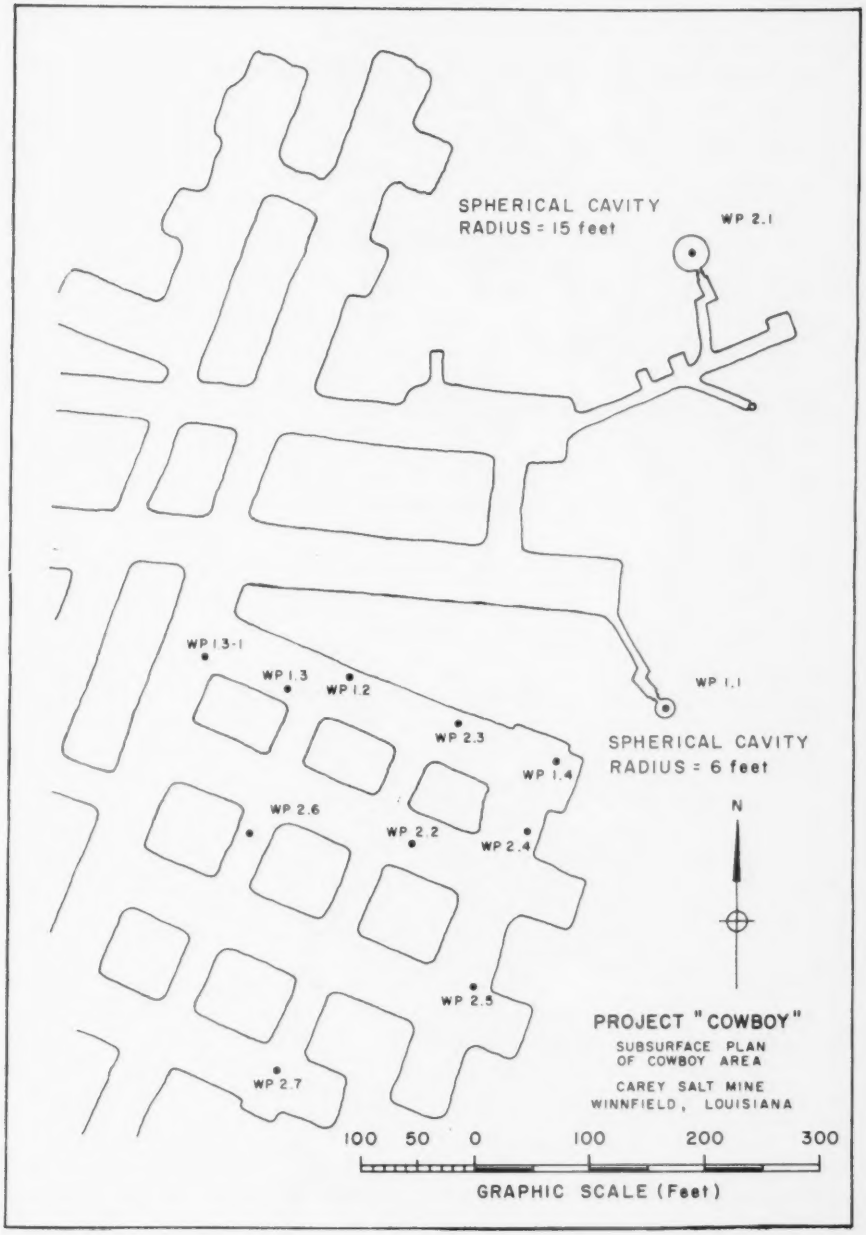

FIG. 4. Map of Cowboy portion of the mine workings showing working points (W.P. 2.1, W.P. 1.1, W.P. 1.3-1, etc.).

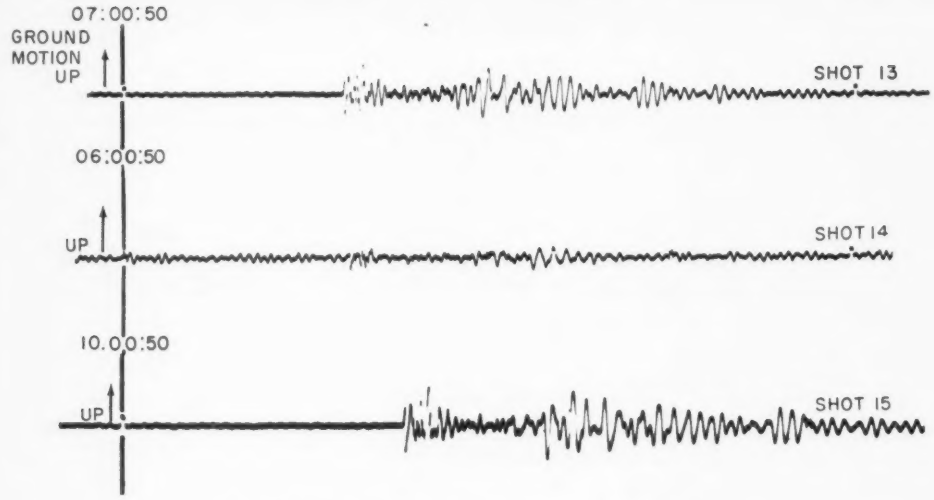

FIG. 5. Station 5, Shots 13, 14, and 15, Benioff 0.5 to 10 cps.

relative location of these stations is shown in Figure 3.

Strong-Motion Seismographs

Three components (vertical, radial, and transverse) of acceleration and the two horizontal components of displacement were recorded by standard strong-motion instrumentation of the U. S. Coast and Geodetic Survey (USC&GS) (Cloud and Carder, 1956).

The accelerometer pendulums were operated at a free period of 0.15 sec and a damping ratio of 10 to 1. Direct photographic paper recording at a speed of 2 in/sec was used with timing marks every second. As all observed frequencies were higher than the pendulum frequency, displacement was actually measured.

The Carder displacement pendulums were operated at a free period of 1.0 sec and a damping of 10 to 1. Recording speeds and time marks were the same as for the accelerometers.

These strong-motion instruments were operated by the USC&GS. Because the gain was fixed for the entire series and, in particular, could not be varied between tamped and decoupled shots of the same yield, the data obtained were not especially useful for decoupling determinations. They are, however, fundamental to near-surface ground-motion measurements of tamped shots in a halite medium.

Recordings from these seismographs are primarily of use for study of tamped explosions in a salt medium. The three strong motion stations duplicate the geometry of three analogous stations of an earlier experiment in a different halite medium. Only Shots 12, 14, and 15 permit decoupling estimates for these instruments. Seismographs that do not have variable gain are of relatively little use for a series of explosions over a wide range of effective yields.

Benioff Variable-Reluctance Seismographs

Three components (vertical, radial, and transverse) of the large, observatory-type Benioff variable-reluctance seismometers were operated with free periods of 1 ± 0.02 cps and a damping 0.65 of critical. The outputs drove 5-cps galvanometers in Geotech Mark I or II 35-mm film recorders. The fourth channel was used to record WWV timing signals through a 20-cps galvanometer. The drum rate was 1.25 mm/sec with timing marks every 10 seconds except at the minute. These seismographs were operated by the USC&GS and the United States Air Force.

In addition to the standard system just described, six small Benioff variable-reluctance seismometers were also used for comparison with the large Benioff. Four vertical seismometers, Geotech Model 4681, and two horizontal seismometers, Geotech Model 6102, were installed.

Relative response curves and phase shift curves are effectively the same as for the large Benioff for frequencies less than 20 cps. These instruments were quite field-worthy, gave excellent visual agreement with the comparable larger Benioff, and are preferred to the large Benioff seismometers for field use.

Shots 12 and 14 were the only decoupled shots observed on the Benioff seismographs. On lower effective yield shots only minimum values of decoupling could be determined. This was done by assuming that the signal for the decoupled shot was equal to the background microseismic activity. The ratio of the signal from the tamped shot to the microseisms at the predicted arrival time of the expected signal from the decoupled shot is taken as a minimum value of decoupling.

Portions of the records of the Benioff seismograms for Station 5 are given in Figure 5. The comparison of the seismograms from Shots 13 and 15 permits an estimate of the reproducibility of seismic data or the effect of relatively small variations in position of the shotpoint.

Low-Frequency (2 to 20 cps) Seismometer Arrays

Six low-frequency (2 to 20 cps) vertical-component seismometers (National 19 L) were placed 200 ft apart on a radial line from Surface Zero. The natural frequency was about 2.00 ± 0.05 cps and the damping was about 0.65 of critical. Precise values were determined for each seismometer. Amplification was by National M/N 25-C amplifiers without AVC. Low-frequency filtering was determined by the seismometer; high-frequency filtering was down 6 db at 24 cps. The data were recorded on photographic paper at $4\frac{3}{4}$ in/sec with timing lines at 0.01-sec intervals. (Magnetic tape recording was also used at Stations 4 and 6.) The overall relative particle velocity response is given as Figure 6. These arrays were operated by National Geophysical Co. under contract to the USC&GS.

Portions of some of the seismograms for these systems are given in Figure 7. An estimate of decoupling may be obtained by visually estimating the ratio of the amplitudes recorded from the tamped shot to the amplitudes recorded from the corresponding decoupled shot. This ratio, when multiplied by the gain correction factor given at left center of the figure ($\times 8$), is an estimate of the decoupling. (Relative gain is denoted by decibels above an arbitrary level.)

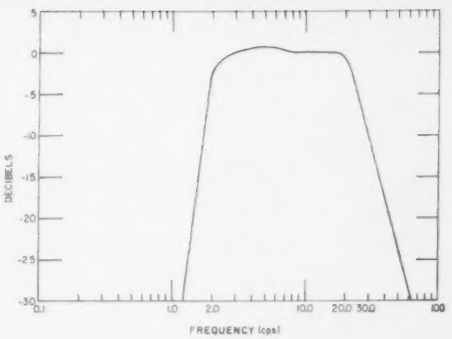

FIG. 6. Relative velocity response of National low-frequency array.

High-Frequency (20 to 100 cps) Seismometer Arrays

These arrays were placed side by side with the high-frequency seismometer arrays. The vertical component seismometers were National 14-A having a natural frequency of about $8\frac{1}{2}$ cps and a damping of about 0.65 critical. Precise values were determined for each seismometer. The outputs of these seismometers were amplified by National M/N 25-C amplifiers without AVC. No low-frequency filtering was done. High-frequency filtering was off 6 db at 150 cps. Recording was done on photographic paper at 10 in/sec with timing lines at 0.01-sec intervals. (Magnetic tape recording was also achieved at Stations 4 and 6.) The overall relative particle velocity response curve is given as Figure 8. These arrays were operated by National Geophysical Co. under contract to the USC&GS. Portions of some of the seismograms obtained from these arrays are given in Figures 9 through 12. Records at Stations 6 and 7 were sometimes poor due to generator interference.

Twelve-Element Seismometer Arrays—Stations Surface Zero and A for Shots 1, 2, 3, and 4

These arrays of seismometers were the visual commercial reflection equipment with no low cut and high cut at 100 cps. No AVC was used. The seismometers were National 14-A having a natural frequency of 8.5 cps and damped approximately 0.65 of critical. Timing lines were every 0.01 sec, paper rate was 10 in/sec, and the relative response particle velocity for the total system was approximately that given in Figure 6. These ar-

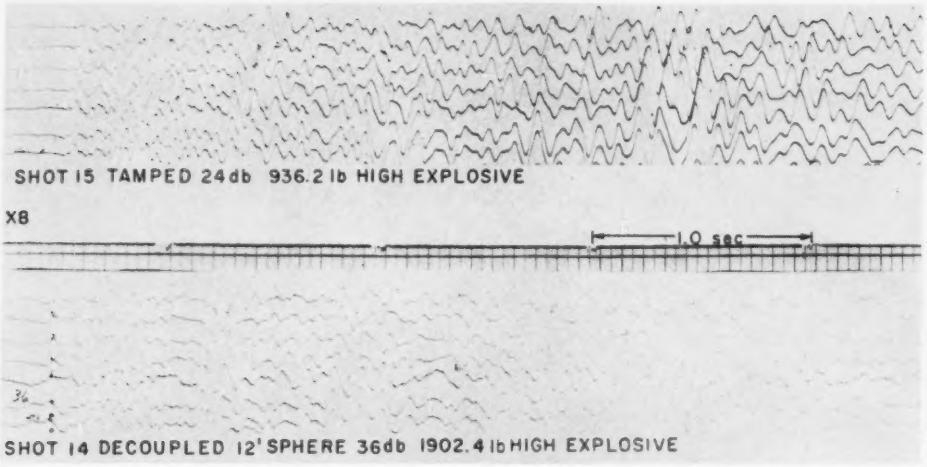

FIG. 7. Station 6, Shots 15 and 14. Low frequency. Six vertical detectors spaced 200 ft apart on radial line starting 44,720 ft from Surface Zero.

rays were operated by National Geophysical Co. under contract to the USC&GS.

Press-Ewing Seismometers

Three components (vertical, radial, and transverse) of long-period seismometers, Sprengnether M/N LH 1002 and LH 1000, were operated. The seismometer had a free period of 15 sec and was overdamped; the galvanometer had a free period of 80 sec and was critically damped. Photographic recording at 30 mm/min was used with time pips every minute. The relative particle velocity response curve is shown in Figure 13. These instruments were operated by the USC&GS in consultation with Lamont Geological Observatory of Columbia University. This was the first time that such instruments had been used in a field effort. The instruments are field-worthy for the stated operating periods.

As none of the shots were recorded on these long-period instruments, no decoupling determination is possible. Sample records are given, however, in Figure 14 to provide information on microseismic background level in the test site area. These seismograms demonstrate the feasibility of fielding long-period seismographs for explosion seismology.

Magnetic Tape Recording

Ampex FR-114 1-inch magnetic tape recorders were operated at 30 ips. Data were frequency modulated on a carrier of 27 kc using a channel for each detector, hence ±40 percent deviation was permissible. Recording was done from 1 minute before shot time to 14 minutes after shot time. Channels 1 through 6 recorded the six elements of the high-frequency arrays; channels 7 through 12 recorded the six elements of the low-frequency array. Station WWV was recorded on channel 13. The 60-cps signal driving the recorder was recorded on channel 15 to permit drift correction during playback.

A high-level instrument noise of 180 cps made these recordings at Station 4 for Shots 5 through 11 less useful. Playbacks of these tapes were directly comparable to the photographic paper records.

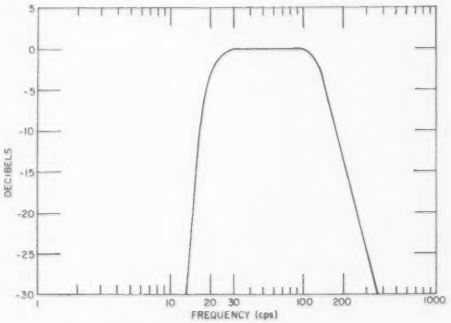

FIG. 8. Relative velocity response of National high-frequency array.

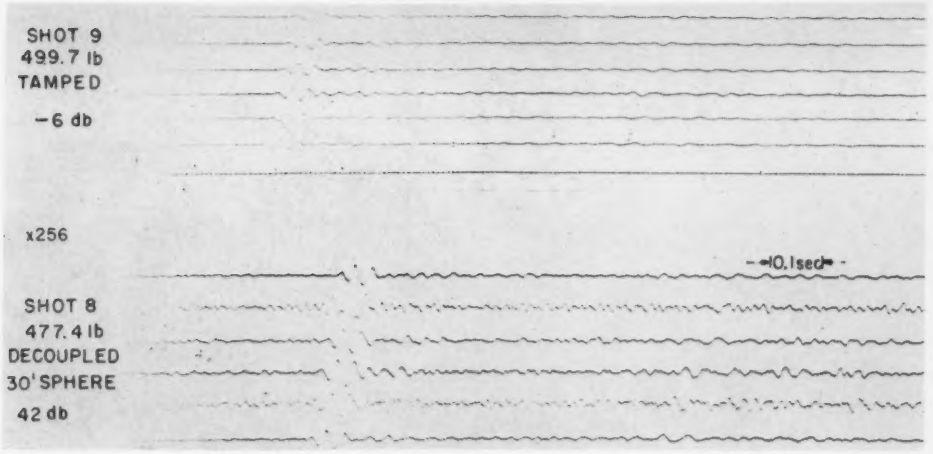

FIG. 9. Station 5, Shot 9 vs. 8. High frequency. Six vertical detectors spaced 200 ft apart on radial line starting 22,110 ft from Surface Zero.

Full-size copies of any of the original records may be obtained upon request from Director, U. S. Department of Commerce, Coast and Geodetic Survey, Washington 25, D. C.

Seismic Measurements by Other Organizations

All surface seismometry was coordinated by the USC&GS. Collaborating groups participating in Project Cowboy were

(a) University of Michigan, Ann Arbor, Michigan;
(b) Atomic Weapons Research Establishment, Aldermaston, England;
(c) Southwestern Louisiana Geophysical Society, Lafayette, La.; and
(d) Texas Instruments Inc., Dallas, Texas.

Data obtained by these agencies are not presented in this report.

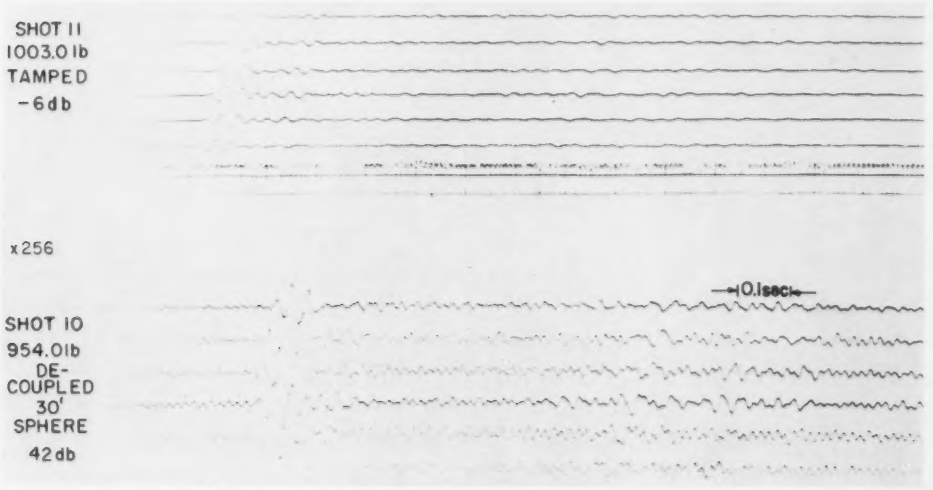

FIG. 10. Station 5, Shot 11 vs 10. High frequency. Six vertical detectors spaced 200 ft apart on radial line starting 22,110 ft from Surface Zero.

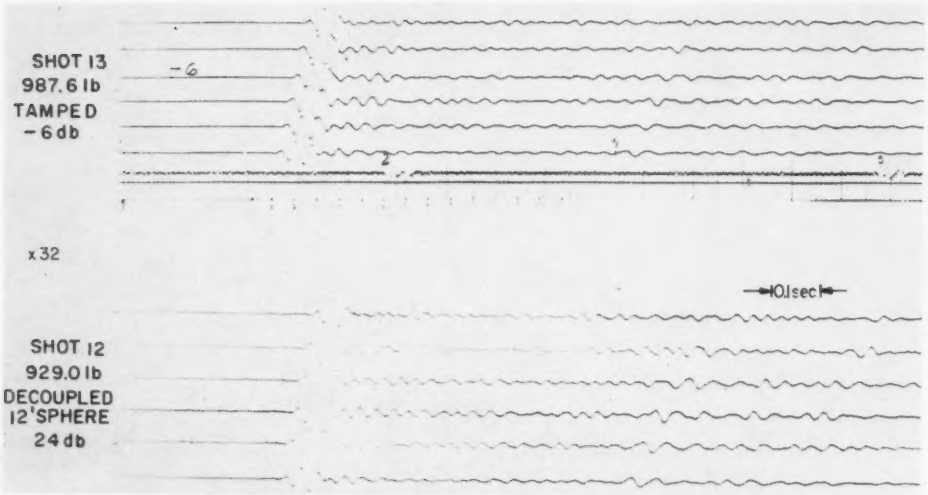

FIG. 11. Station 5, Shot 13 vs 12. High frequency. Six vertical detectors spaced 200 ft apart on radial line starting 22,110 ft from Surface Zero.

ANALYSIS PROCEDURES

As the theory treats the ratio of Fourier transforms, it was necessary to calculate the Fourier transform of the observed seismograms. To do this on an electronic digital computer (EDC) required digitization of the seismic traces.

Digitization of Seismograms

Photographic Paper Seismograms.—Records were individually placed on the reading surface of a Benson-Lehner Oscar connected to an IBM punched-card output. These cards were suitable for direct input to the electronic digital com-

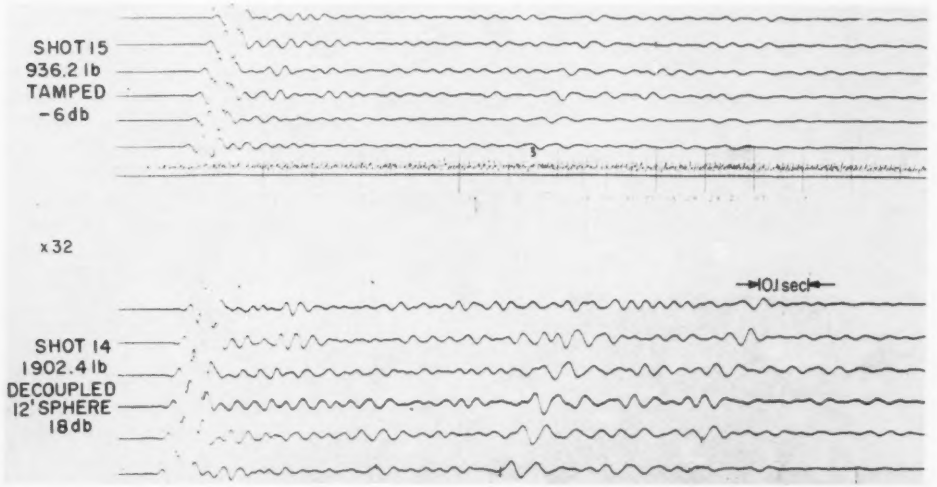

FIG. 12. Station 5, Shot 15 vs 14. High frequency. Six vertical detectors spaced 200 ft apart on radial line starting 22,110 ft from Surface Zero.

puter, an IBM 704 or 709. Because recording was done at two levels of sensitivity, no difficulty of overlap of traces was encountered. Two-hundred twenty-five traces of the photographic paper seismograms have been digitized in this manner.

Photographic Film Seismograms.—For the 35-mm film, field procedure permitted only one trace per strip during a shot event. Insofar as possible, the single trace was centered on the film. The portion of the trace containing the signal from the shot was contact-printed to form a negative film. This was placed in an optical-electronic digitizer under development at the Lawrence Radiation Laboratory (Adams and Allen, 1961). This device is a combination of a cathode-ray tube, a photomultiplier tube, and an electronic digital computer.

The physical arrangement is shown diagrammatically in Figure 15. The sequence of events is as follows: The electron beam is directed to a position on the film, say X_0, Y_0, in a rectangular coordinate grid system. If the trace does not pass through that point, then a systematic search is conducted to locate it by sequentially inspecting points on the film. When a point is found through which the trace passes, then the photomultiplier will be excited. A pulse will be supplied to the computer causing the values of the coordinates (X_1, Y_1) of the point to be stored. A systematic search procedure for following the trace is then used. Because of the width of the trace and halation of the film, the edges of the trace are found and then averaged to obtain an estimate of the

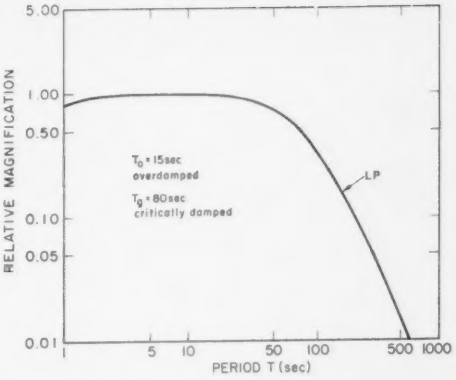

FIG. 13. Relative velocity response of Press-Ewing seismographs. (After G. Sutton and J. Oliver, Annales de Geophysique, 1960)

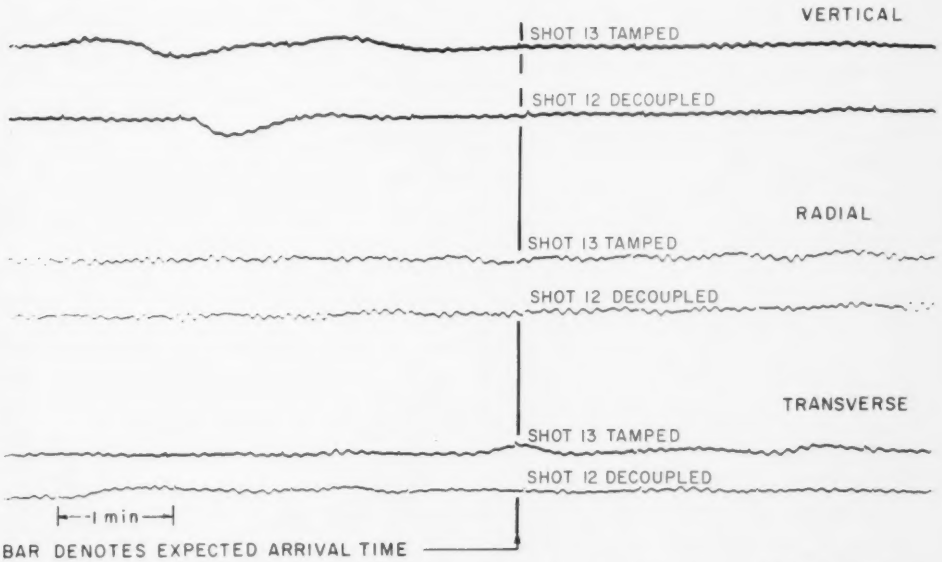

FIG. 14. Station 11, Shots 12 and 13. Press-Ewing. $T_s = 15$ sec; $T_g = 90$ sec. Tamped = 929.0 lb high explosive; decoupled = 987.6 lb high explosive. 323,820 ft from Surface Zero.

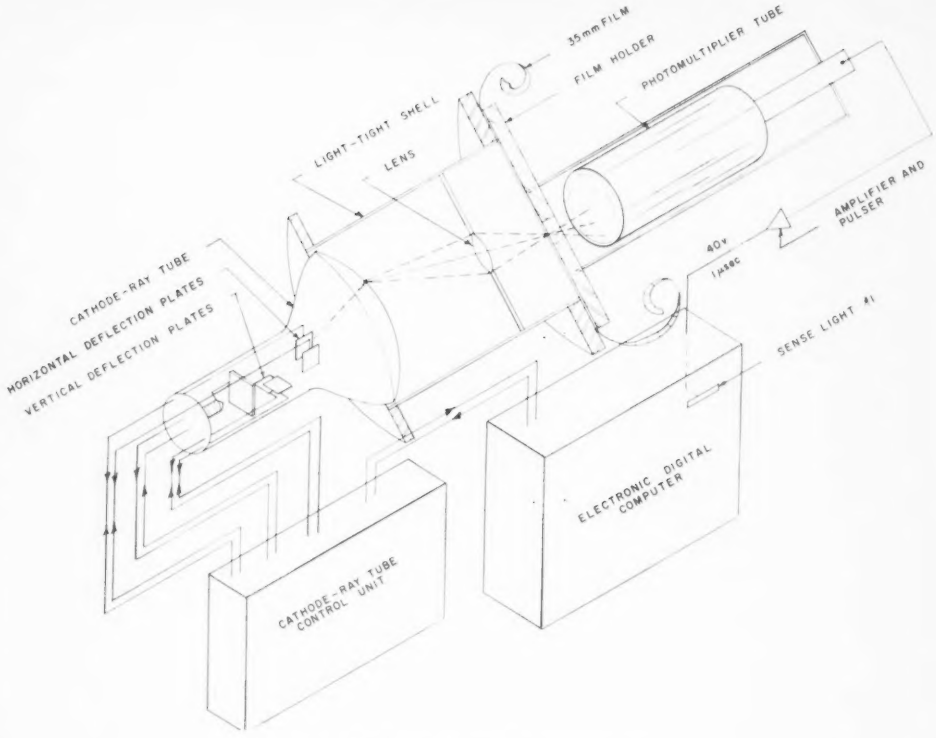

FIG. 15. Diagram of the Eyeball digitizing unit.

central value on the amplitude coordinate.

Both amplitude and time increments are uniform with resolution of 1024 points per 0.75 inch. A 0.75-inch section of film is analyzed, the film strip is advanced 0.75 inch, and the new section located in the scanning area is digitized. Automatic advance is not yet possible, manual advance presently being necessary.

This electronic film reader is nicknamed "Eyeball."

Magnetic Tape Recordings.—Lockheed Aircraft Corporation at Sunnyvale, California, performed analog-to-digital conversion of the FM-recorded data. Each channel was digitized for about a 100-second interval. Channels 1 through 6, having the high-frequency (20–100 cps) array data, and channels 7 through 12, having the low-frequency (2–20 cps) array data, were digitized at 500 samples per second. These rates provided five samples per cycle of the highest data frequency of interest, $2\frac{1}{2}$ times the theoretical minimum.[1] All tape recorded data have been processed in this manner.

Time from WWV had been recorded on channel 13 during the shot event. The times of zero crossover (in a relative sense only) of the WWV tone of 400 cps were determined and provided in digitized form to permit correction for wow and flutter.

Channel 14 recorded the 60-cps signal used to drive the synchronous motors during the shot event. By using this signal on playback as a standard to which to phase-lock the oscillator generating playback power, corrections compensating for low-frequency drift could be made.

[1] The theoretical minimum is taken to be twice the Nyquist folding frequency. A parameter study for the variation of the frequency spectrum as a function of samples per cycle has also been made. It appears that *for these data* five samples per cycle of the highest frequency actually being recorded provides a Fourier spectrum which does not significantly improve *for the analysis being conducted* when the sampling rate is increased. The study covered rates from 1 to 25 samples per cycle.

Identification of Phases on Seismograms

To determine the ray path traversed by a particular signal pulse on the seismogram, a truncated cone has been taken as the shape of the salt dome[2] (Musgrave, Wooley, Gray, 1960) and travel times for various likely paths, especially for critically refracted waves, were determined for a given station. Correlation of the predicted sequence of arrivals with the observed seismograms usually permits identification.

Another feature assiting in the identification of phases is the apparent velocity across the array of a particular pulse. As there are no steep dips in the area, the apparent velocity should be approximately the velocity of the refracting horizon. A few of the observed values were much larger. Any variation in the apparent velocity is most easily explained by the dip of the refracting horizon below the receiver. In the present situation, all observed apparent velocities seem to be high. An alternate explanation of varying apparent velocities is variation in the thickness of the weathered zone. Weathering shots were not made for any of the arrays. However, the region is not expected to differ significantly outside the salt domes. Again, why the values are consistently high is not clear.

Computations

Fourier Transform.—The digitized data were processed by a code named Fotos (Fourier Transform of Seismograms) that (1) accepts any one of the various modes of data input; (2) computes the Fourier transform,

$$U(t) = 1/\pi \int_0^\infty a(\omega) \cos \omega t \, d\omega + 1/\pi \int_0^\infty b(\omega) \sin \omega t \, d\omega, \quad (19)$$

where

$$a(\omega) = \int_0^\infty U(t) \cos \omega t \, dt$$

and

$$b(\omega) = \int_0^\infty U(t) \sin \omega t \, dt,$$

[2] Although the shape is actually unknown, a typical shape has been assumed. The truncated cone is preferred to the cylinder so often used to represent a salt dome.

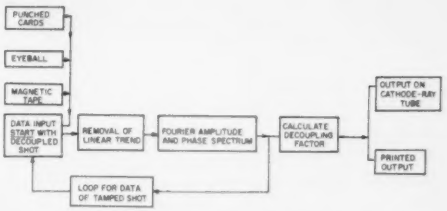

FIG. 16. Data flow through Fotos code.

by numerical techniques; and (3) stores the results on a high-speed printer output tape and on an output tape for the cathode-ray-tube data display output.

The flow chart of the data is shown diagrammatically in Figure 16. Sensitivities of the seismometer, the amplifier, the recorder, and the digitizer can be corrected for and the ratio of tamped shot to decoupled shot determined as a function of frequency.

The numerical computation of the Fourier transform[3] used a quadratic fit through each three successive points which was then integrated by parts over the two intervals. Using the numerical first and second derivatives, the computations are

$$a_n = \frac{M^2}{8\pi^3 n^3} \sum_{l=3}^{M-3} (Y_{l-2} - 2Y_{l-1} + 2Y_{l+1} - Y_{l+2}) \sin nx_l. \quad (20)$$

$$b_n = \frac{M^2}{8\pi^3 n^3} \sum_{l=3}^{M-3} (Y_{l-2} - 2Y_{l-1} + 2Y_{l+1} - Y_{l+2}) \cos nx_l. \quad (21)$$

Using special terms for evaluation at the ends, the error appears to be less than 3 percent in a test case.

Because of the digitizing techniques it was found necessary to perform a removal of linear trend. Otherwise the energy at the very low and very high frequencies was distorted. Examples of the information that the Fotos code provides are given in the original laboratory report UCRL-6086. First the digital input data are plotted back to assure that the correct input data are being used. The Fourier amplitude and phase spectra are obtained in relative units for comparable traces from the tamped shot and the decoupled shot. All but a negligible amount of the work done

[3] Share code AAHAN2 formed the basis for Fotos.

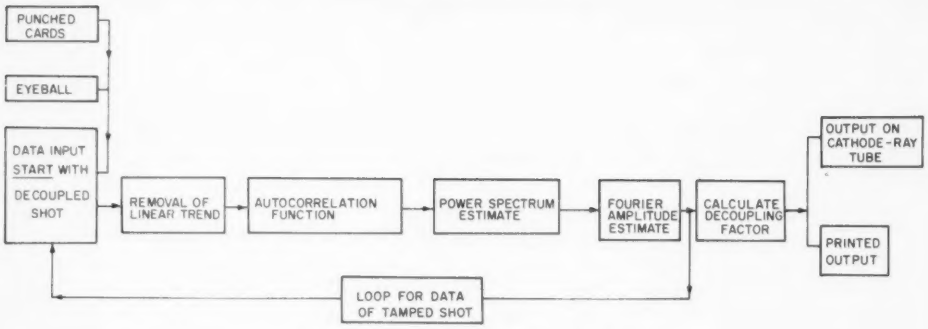

FIG. 17. Data flow through Shaker code.

for this report was performed in relative units, primarily to eliminate possible sources of error in deriving decoupling. The reductions used in going from relative to absolute units are identical for the seismograms from both the tamped shot and the decoupled shot and can therefore be neglected for the purposes of this report. The ratio of the amplitude spectrum for the tamped shot to the amplitude spectrum for the decoupled shot as a function of frequency, as specified by equation (15), gives the decoupling factor $F(f)$ (termed D.F. in the figures).

Power Spectrum.—The Fourier transform is most suitable for processing seismic signals. However, because the microseismic background during the recording of the decoupled lower-yield shots was of the same order as the signal level, it was necessary to study the effects of this noise. As seismic noise is approximately a stationary phenomenon, that is, it is not related to a source time, having no beginning or end, Fourier transformation is not theoretically suitable. For this reason a code, named Shaker,[4] for energy density determination via the autocorrelation function, was evolved. Input and output were as for Fotos, except magnetic tape input was not used. Removal of linear trend was retained. As previous investigators of the analysis of seismic data by statistical means had found this power spectrum method useful (Tukey, 1959; and Wadsworth, et al, 1953), a procedure to compute the decoupling ratio via this route was used. This was possible because of the relation between the power spectrum and the Fourier transform.

The flow of data through the power spectrum code, Shaker, when used to compute decoupling, is shown in Figure 17.

The computation of the power spectrum is performed using the method of Blackman and Tukey (1959, p. 117, ff.). The autocorrelation function is evaluated:

$$C(r) = \frac{1}{n-r} \sum_{q=0}^{n-r} X_q \cdot X_{q+r} \qquad (r = 0, \cdots M), \quad (22)$$

where n is the total number of X values and r is the lag. The energy estimate of the spectrum is then

$$U(r) = \frac{\delta}{M} \sum_{q=1}^{M-1} 2\left(1 + \cos\frac{q\pi}{M}\right) \cdot \cos\frac{rq\pi}{M} \cdot C(r), \quad (23)$$

where

$$\delta = 1 \qquad 0 < K < M$$

and

$$\delta = 1/2 \qquad 0 = K = M.$$

This estimate is frequency dependent according to

$$U(r) = U\left(f_{Ny}\frac{r}{M}\right) = U(f), \quad (24)$$

where f_{Ny} is the Nyquist folding frequency, the highest frequency at which information is recoverable from digitized stationary data by power spectral methods.

[4] Share code CS TUKS formed the basis for Shaker.

Now the energy estimate of the power spectrum is related to the Fourier spectrum in the limit by (N. Wiener, no date, p. 150)

$$U(r) \propto F^2(\omega), \tag{25}$$

so it is possible to estimate decoupling factors from power-spectral analyses by taking the square root of the ratio of the power spectrum of the tamped shot to the power spectrum of the decoupled shot,

$$F(\omega) \simeq \left[\frac{U_T(r)}{U_D(r)}\right]^{1/2}. \tag{26}$$

Examples of the information that a processing by the Shaker code of the digitized data provides are shown in UCRL-6086. During a Fotos run, portions of the digital input data are plotted back to assure that the data being treated are those desired and are comparable, by visual comparison, with the original seismogram trace. Therefore, this is not done in Shaker. The autocorrelation and power spectrum for each trace is then determined in relative or absolute units. The 90 percent bound on the power spectrum is designated by points above and below the best estimate of the power spectrum density. The decoupling factor as a function of frequency, the major result for the purposes of the Cowboy decoupling experiment, is obtained by equation (26).

Because the yields of the shots being compared were not exactly equal, it is necessary to modify equations (15) and (26) for this effect. Assuming that the amplitude coefficient at a particular frequency is directly proportional to yield (Latter, Martinelli, and Teller 1959), we may use

$$F(\omega) = \frac{\hat{U}_T(\omega)}{\hat{U}_D(\omega)} \cdot \frac{W_D}{W_T} \tag{27}$$

and

$$F(\omega) = \left[\frac{U_T(r)}{U_D(r)}\right]^{1/2} \cdot \frac{W_D}{W_T}, \tag{28}$$

respectively.

In addition, the decoupling for zero frequency has either been left unplotted or set equal to zero. This was necessary since removal of linear trend was used on all data.

Faulty recording, digitizing, or processing is detected in Fotos by (1) oscillation of the corresponding phase spectrum, (2) extreme irregularity in the Fourier spectrum, and (3) by failure of the spectrum to cut off outside the designed passband; and in Shaker by (1) inconsistencies across the several traces of an array, (2) failure of the power spectrum to drop off outside the designed passband, and (3) difference in the autocorrelation function for the tamped and decoupled shots. The two codes tended to check one another.

It is sometimes possible to consider decoupling outside the bandpass frequency range because the cutoffs on either side were presumably identical for each shot of the pair being compared.

The effect of the background microseismic activity on the determination of decoupling needs to be considered. The noise will affect the amplitude or energy determined for the decoupled signal and therefore needs to be subtracted in the analysis. Thus, the decoupling factor needs to be defined as

$$F(f) = \frac{\hat{U}_T(f)}{\hat{U}_D(f) - \hat{N}(f)}, \tag{29}$$

where $\hat{N}(f)$ is the Fourier coefficient of the noise at frequency f. Such a study was made for traces on one low-level shot pair, 3-4, and will be described later. It is found that the decoupling is always *decreased* by neglecting the effect of the noise (since it is *assumed* that the noise always adds). The effect can be up to 40 percent of the decoupling factor.

We now apply these methods to the surface seismograms obtained during Project Cowboy.

RESULTS AND DISCUSSION

The results presented in this section are based on treating the entire length of the signal as a unit for the analysis. Thus, the Fourier spectrum or power spectrum was derived for the entire trace, not just for a particular pulse. Particular emphasis has been given the high-frequency traces as these seismograms were well recorded at most stations; contained the data closest to or about the dominant frequency, ω_0, of the particular shot; and the high frequencies appeared to be almost as coherent as the lower frequencies at the more distant stations such as Station 6.

The results will be treated in order of increasing steady-state cavity pressure, estimated by (Latter et al, 1961, equation 1)

$$p(\text{bars}) = 3 \times 10^5 \frac{W(\text{tons})}{V(\text{ft}^3)}, \qquad (30)$$

the derivation of which assumes $\gamma = 1.2$. The effect of an alternate value of gamma is absolute, not relative. The steady-state cavity pressure corresponding to each decoupled yield is given in Table IV. The order of presenting the results by steady-state pressure will be, therefore, decoupled Shots 5, 2, 8, 10, 3, 12, and 14.

It should be remembered that all of the results in this section are minimal values of decoupling since the noise energy has not been subtracted from the energy determination for the decoupled shot. This effect is very significant for the shot pairs having high decoupling and much less meaningful for the shot pairs having low decoupling.

Shot Pair 5-17

This was a pair of nominal 200-lb shots. The decoupled shot was in the 30-ft-diam. cavity. Because the tamped Shot No. 7 overloaded the recording system, Shot No. 17 was used as the comparable tamped shot. All six *hf* traces were analyzed by both Fotos and Shaker. Results for trace 3 as recorded at Station 4 are shown in Figure 18. Note that Shaker tends to smooth over the peaks given by Fotos. This is as expected in theory. Because of the complexity of the Fourier spectra obtained in this work, the power density estimates have been very helpful in showing trends.

The fact that the decoupling factor goes up for the frequency band 20 to 50 cps is outstanding. Although the falloff towards higher frequencies may be due to background noise, as suggested by occasional peaks at higher frequencies, the cut towards 10 cps is considered real and consistent.

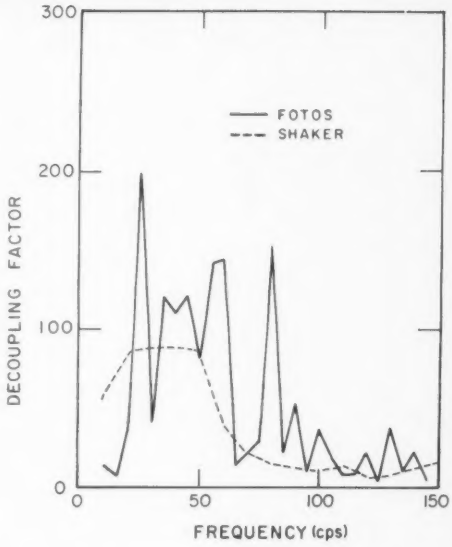

FIG. 18. Station 4, Shot 5 vs 17, Trace 3.

Table IV. Steady-State Pressure for Decoupled Shots

Decoupled Shot	Yield (lb)	Cavity radius (ft)	S.S.P.* (bars)	S.S.P. / O.P.†
2	20	6	3.3	0.057
3	100	6	16.5	0.29
5&6	200	15	2.0	0.035
8	477	15	4.7	0.083
10	954	15	9.5	0.16
12	929	6	154	2.7
14	1902	6	316	5.5

* S.S.P. = steady-state pressure.
† O.P. = overburden pressure measured by the Bureau of Mines (1960, p. 10–11), and averaged about 850 psi (57.8 bars).

Shot Pair 2-1

This was a pair of nominal 20-lb shots with the decoupled shot in the 12-ft-diam. cavity. For this pair of shots, the Surface Zero station was severely bothered by 60-cps pickup from an overhead power line. However, it was possible to get some fair estimates from records made at Station A even though the system was overdriven. The decoupling is about 80. Because the signal was not observed for the decoupled shot, this is a minimum. Furthermore, since Station A is at a relatively small distance from Surface Zero, about 5,000 ft, interference in the waves arriving by different paths creates noticeable change across the array.

Shot Pair 8-9

This was a pair of nominal 500-lb shots. The decoupled shot was in the 30-ft-diam. spherical cavity.

Station 4.—At Station 4 all six *hf* traces were analyzed. Results for trace 6, best exemplifying features considered significant for this array, are given in Figure 19. The peaks in $F(f)$ are between

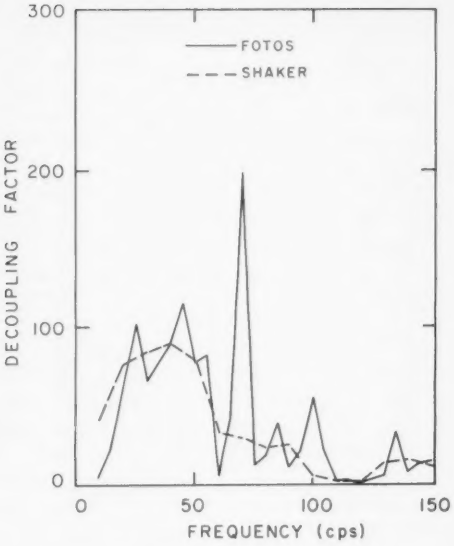

FIG. 19. Station 4, Shot 8 vs 9, Trace 6.

30 and 40 cps in Shaker with average values of about 100. Fotos shows a higher peak value of 120 in the same band. There seems to be a high from 130 to 150 cps that is consistent across the array. The significance of this high is unknown.

Station 5.—All six *hf* traces were run through Shaker. Decoupling versus frequency is given in Figure 20 for trace 2, as machine plotted. The frequency band from 10 to 45 cps is very similar for all traces. There is a definite decrease from a value of about 175 at 45 cps down to 100 at 20 to 25 cps, then a slight rise to 10 cps, falling off below this. Above 45 cps, decoupling falls off sharply to 50 to 60 cps, vacillating mildly and apparently arbitrarily for frequencies out to 180 cps.

Shot Pair 10-11

This was a pair of nominal 1,000-lb shots. The decoupled shot was in the 30-ft-diam. sphere.

Station 4.—Only three *hf* traces, 1, 3, and 6, were analyzed as the signal from the decoupled shot is considered much larger than the background noise; hence, extensive "trace averaging"

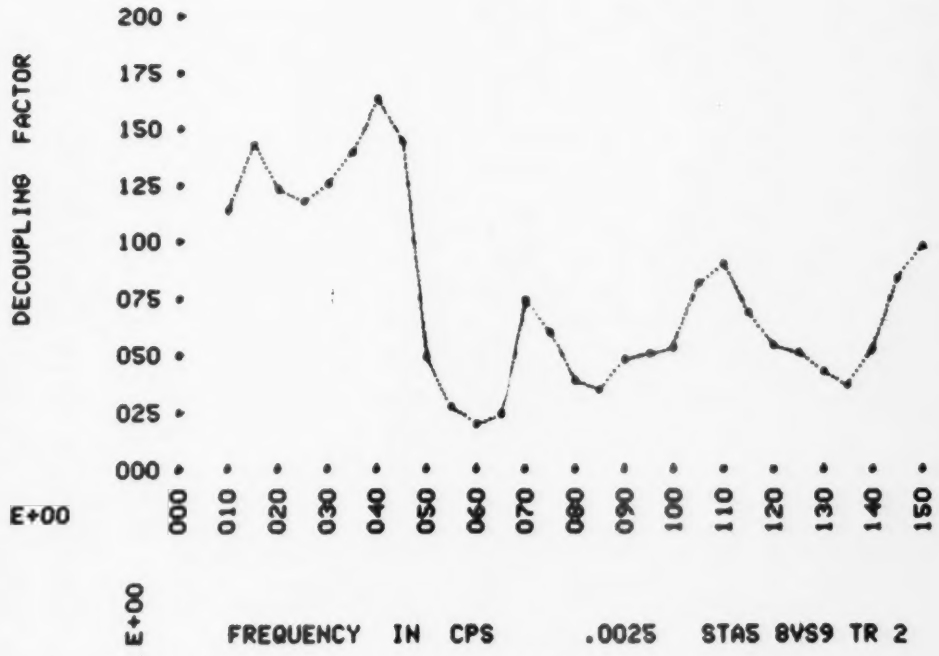

FIG. 20. Station 5, Shot 8 vs 9, Trace 2. From original drawings made directly by the electronic digital computer.

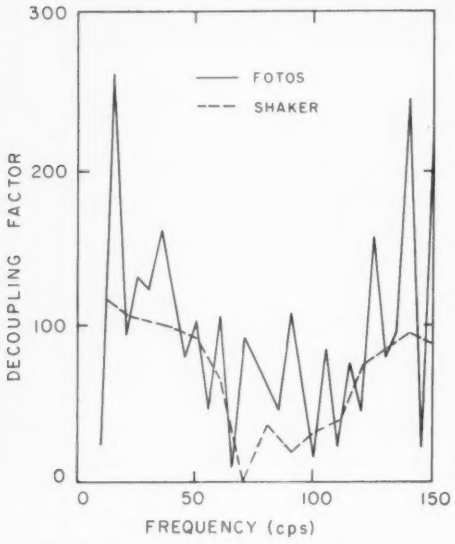

FIG. 21. Station 4, Shot 10 vs 11, Trace 1.

is not necessary. Figure 21 presents the results for trace 1. The highs occurring at 20 to 50 cps and 120 to 150 cps are now well defined, having average decoupling values of 100 and 80, respectively.

Station 5.—All six *hf* traces showed excellent similarity for $F(f)$ from 10 to 45 cps, increasing from 80 at 10 cps to 100 at 45 cps (see Figure 22). Falloff is sharp from 50 to 60 cps, falling to only 20 at 60 cps.

Station 6.—High-frequency traces 2, 4, and 6 were studied. The analyses from Shaker are presented for trace 2 in Figure 23. All three traces show the typical graben feature, with $F(f)$ values of 55 at 10 cps, 40 at 25 cps, and 55 at 45 cps.

Shot Pair 3-4

This pair consisted of two nominal 100-lb shots The decoupled shot was at the center of the 12-ft-diam. cavity.

Station Ground Zero.—The twelve-element array operated at Ground Zero obtained signals from both the tamped and decoupled shots. The decoupled signal was superimposed on a 60-cps noise. For trace 12 this 60 cps was removed, point by point. The decoupling factor then obtained using this corrected trace for the decoupled signal gave a peak of 95 for 30 cps.

Station A.—The $F(f)$ function was determined using Shaker for all twelve traces. Four adjacent end traces, 1 through 4, were significantly lower than the others, averaging about 30 to 35 instead of 50 to 60. Variation with frequency was variable, no trends being consistent. The portion from 10 to 50 cps seemed to be more coherent than higher-frequency sections.

A study of the effect of noise contamination of the recorded signal was made for this shot pair. The noise energy was found for a portion of record just ahead of the signal of the decoupled shot. Assuming the noise to remain of the same strength and character during the signal arrival, then an *upper* bound for the decoupling factor may be found by subtracting the noise energy from the energy of the signal plus the noise. The ratio of tamped to decoupled is then taken. The results for trace 12 are given in Figure 24. Up to 40 percent error seems attributable to the neglect of noise, the value depending upon the spectra of the noise and signal. However, the effect is systematic, causing the values of decoupling to be uniformly *low* when the effect of the noise is neglected.

Shot Pair 12-13

This was a pair of nominal 1,000-lb shots. The decoupled shot was in the 12-ft-diam. sphere, giving a steady-state pressure of about 154 bars.

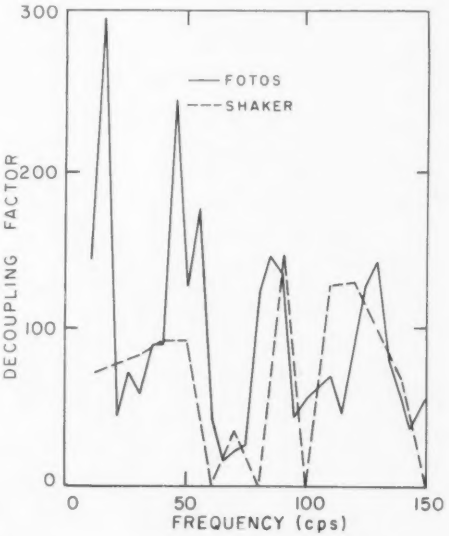

FIG. 22. Station 5, Shot 10 vs 11, Trace 2.

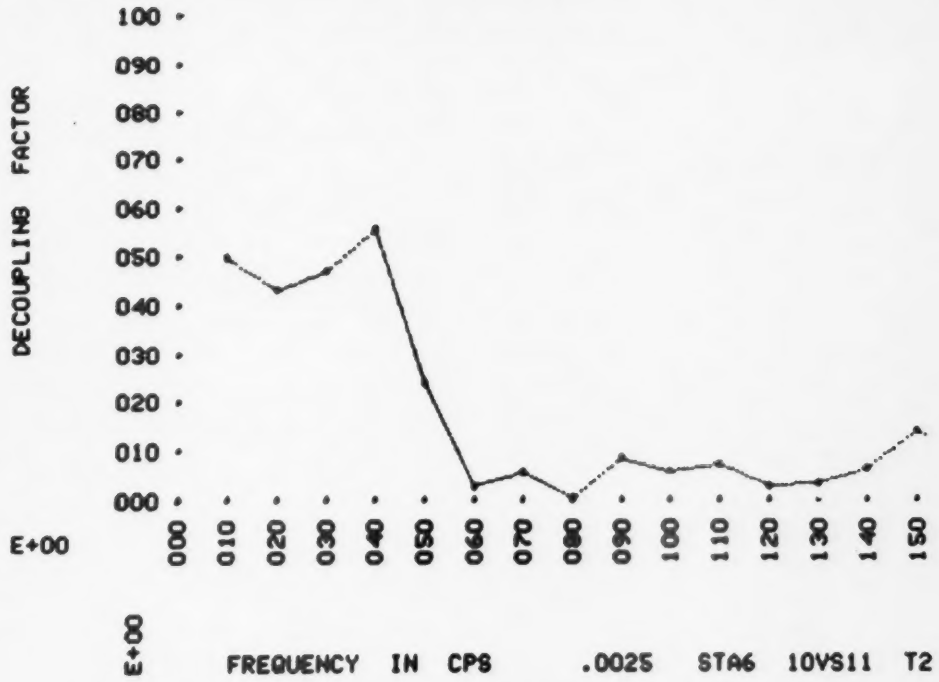

FIG. 23. Station 6, Shot 10 vs 11, Trace 2. From original drawings made directly by the electronic digital computer.

Station 4.—High-frequency traces 1, 3, 4, and 6 were processed by Fotos and Shaker. "Peakedness" is not as severe as on earlier results for lower yield shots (see Figure 25). Averaging the decoupling factor over frequency gives about 25. The hump at higher frequencies still exists, having a lower value, about 18.

Station 5.—The analysis for *hf* trace 1, shown in Figure 26, again gives the sharp decrease in $F(f)$ from 60 at 45 cps down to 20 at 25 cps, rising to 80 at 15 cps then falling off at lower frequencies. Above 45 cps, $F(f)$ has a definite low at 60 cps but nothing consistent above this frequency.

Station 6.—Traces 2, 3, and 4 from the high-frequency seismograms were processed by Fotos and Shaker. The results for trace 4 are shown in Figure 27. The average of the decoupling factor is about 28, being fairly uniform across the array.

Shot Pair 14-15

This pair consisted of a nominal 1,000-lb tamped shot and a 2,000-lb decoupled shot, fired

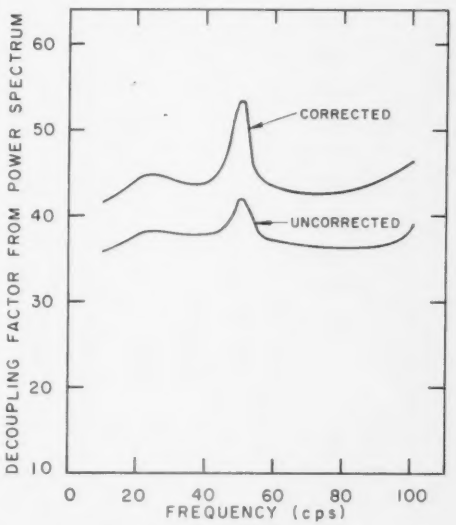

FIG. 24. Station A, Shot 3 vs 4, Trace 12. Effect of noise on $F(f)$.

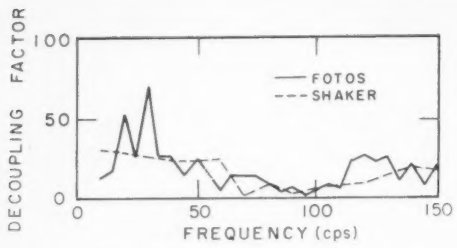

FIG. 25 Station 4, Shot 12 vs 13, Trace 1.

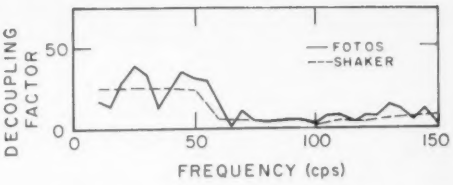

FIG. 27. Station 6, Shot 12 vs 13, Trace 4.

in the 12-ft-diam. cavity and producing a steady-state cavity pressure of about 316 bars. However, the cavity vented through the portal about one-half second after detonation. The amplitudes observed on the seismograms for the 1,000-lb shot were simply doubled for comparison with the decoupled shot, amounting to assuming that amplitude is proportional to yield (see Latter, Martinelli, and Teller, 1959).

Station 4.—High-frequency traces 1, 4, and 6, were run on the Fotos and Shaker codes. Figure 28 gives the results for trace 1. The value of $F(f)$ averaged over frequency is about 10. Indication of a rise at the higher frequency band about 140 cps still occurs.

Station 5.—The analysis for *hf* trace 1 is given in

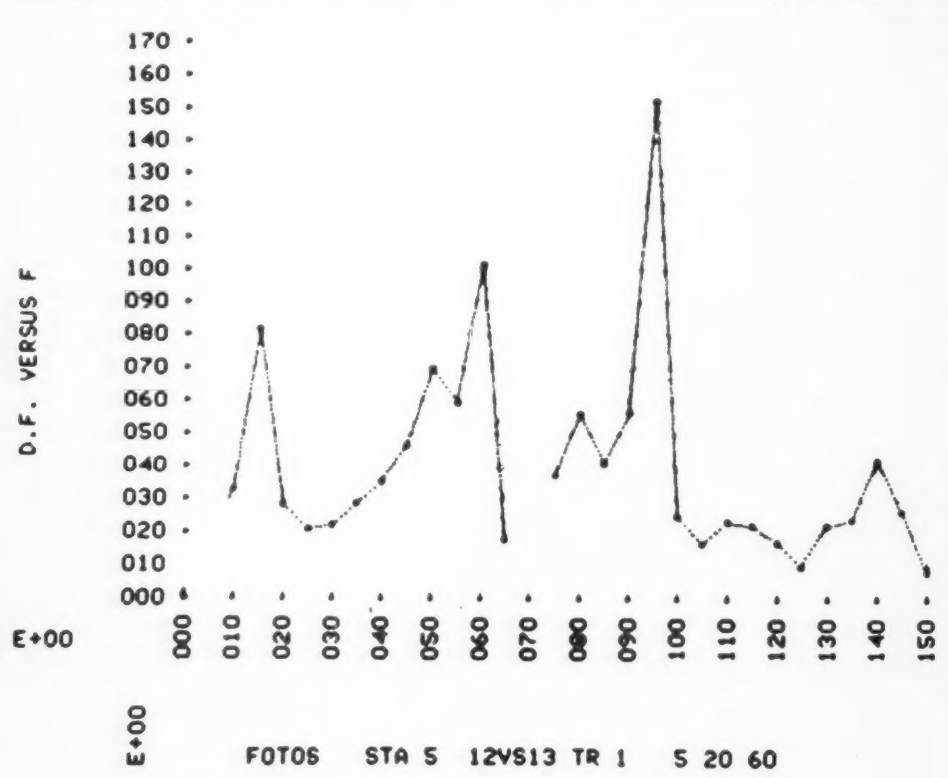

FIG. 26. Station 5, Shot 12 vs 13, Trace 1. From original drawings made directly by the electronic digital computer.

Figure 29 and again shows the graben between 45 cps and 12 cps, the high value of $F(f)$ being about 23 and the low of seven near 20 cps.

Station 6.—High-frequency trace 1 was analyzed and the results are given in Figure 30. The $F(f)$ averaged over frequency is at least 10.

Decoupling Factor Versus Steady-State Pressure

From the foregoing results, the values of decoupling have been abstracted for a given frequency range and plotted in Figures 31, 32, and 33 as a function of steady-state cavity pressure

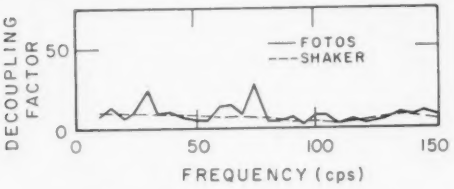

FIG. 28. Station 4, Shot 14 vs 15, Trace 1.

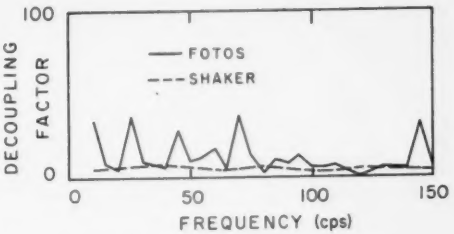

FIG. 29. Station 5, Shot 14 vs 15, Trace 1.

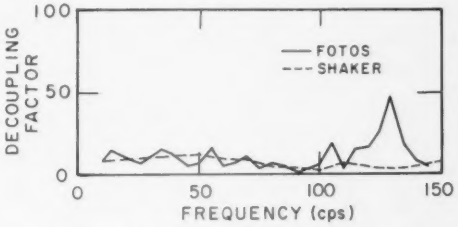

FIG. 30. Station 6, Shot 14 vs 15, Trace 1.

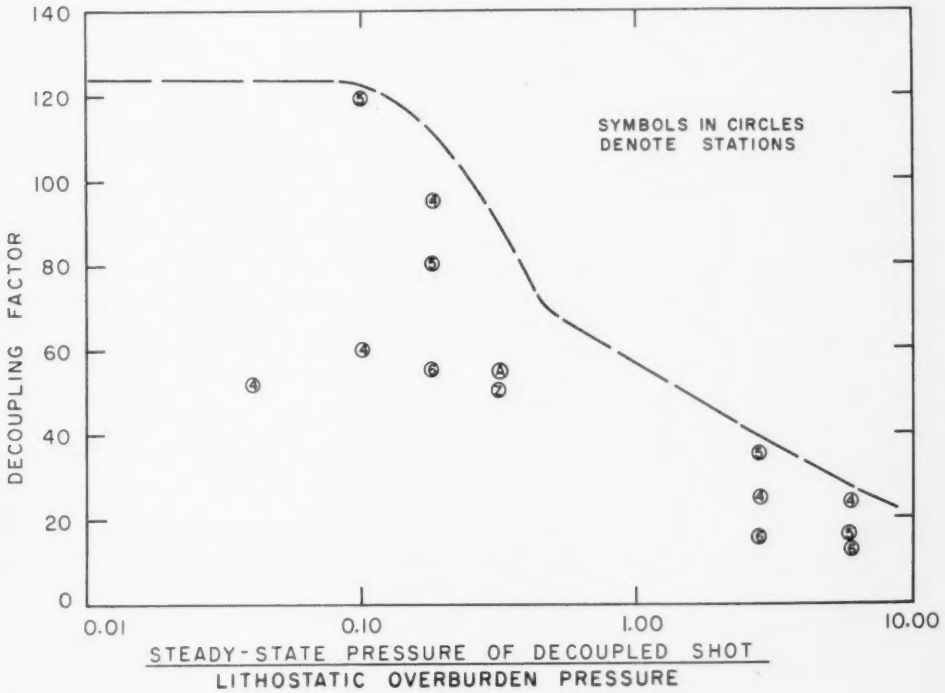

FIG. 31. Minimum decoupling factor at 10 to 20 cps.

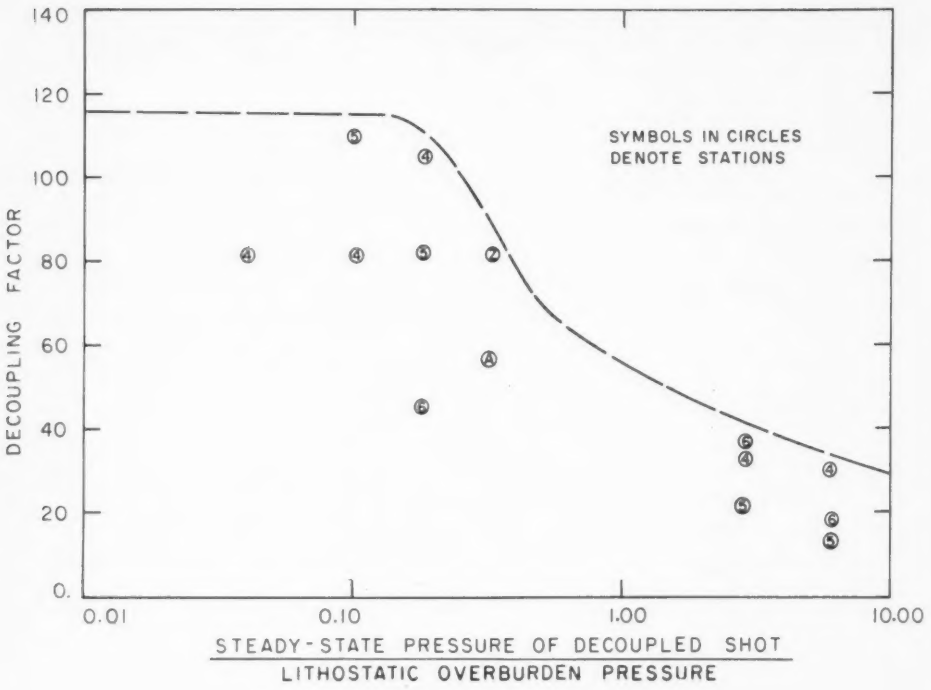

FIG. 32. Minimum decoupling factor at 20 to 30 cps.

normalized to the lithostatic overburden pressure. It is noticeable and regrettable that no values exist between 16 and 160 bars because this is the section in which the function varies and, hence, needs definition. In studying these curves, recall that plotted values should be considered lower bounds because the effect of the microseismic background has been neglected as described previously.

For Station 5, the decoupling curve seems to rise faster for higher frequencies (45 cps) than for lower (20 to 24 cps). They both attain decoupling values of over 100 for pressures of less than 5 bars, the higher frequency (45 cps) attaining this value at 10 bars.

It may be that Station 5 is anomalously high at 154 bars because both Stations 4 and 6 are lower for most frequencies (near the value for 25 cps at Station 5). This would give a slower rise toward the lower pressures, considered more probable in view of the low values observed at Stations GZ and A for the 100-lb pair.

The most unexpected feature of these results is the notable decoupling (10 to 25 and higher) for steady-state cavity pressures far in excess of the lithostatic overburden. To obtain an understanding of this phenomenon, the overburden stress was measured by the Bureau of Mines as a function of depth into the walls of the mine workings (Merrill). A free-field value of about 55 bars for this overburden was determined. Furthermore, the stress distribution was effectively hydrostatic. The stress increased to about 80 bars, $1\frac{1}{2}$ times the free-field value, at the wall of the spherical cavity, a value consistent with elastic theory. Hence, it is concluded that the overburden is close to what was assumed in the theory of decoupling. The mechanism of decoupling for cavities having steady-state pressures greater than the lithostatic pressure has been considered by Nuckolls (1960).

CONCLUSIONS

The set of seventeen chemical explosions conducted in the Carey Salt Mine at the Winnfield Salt Dome has definitely proven that the seismic energy propagating from chemical explosions of

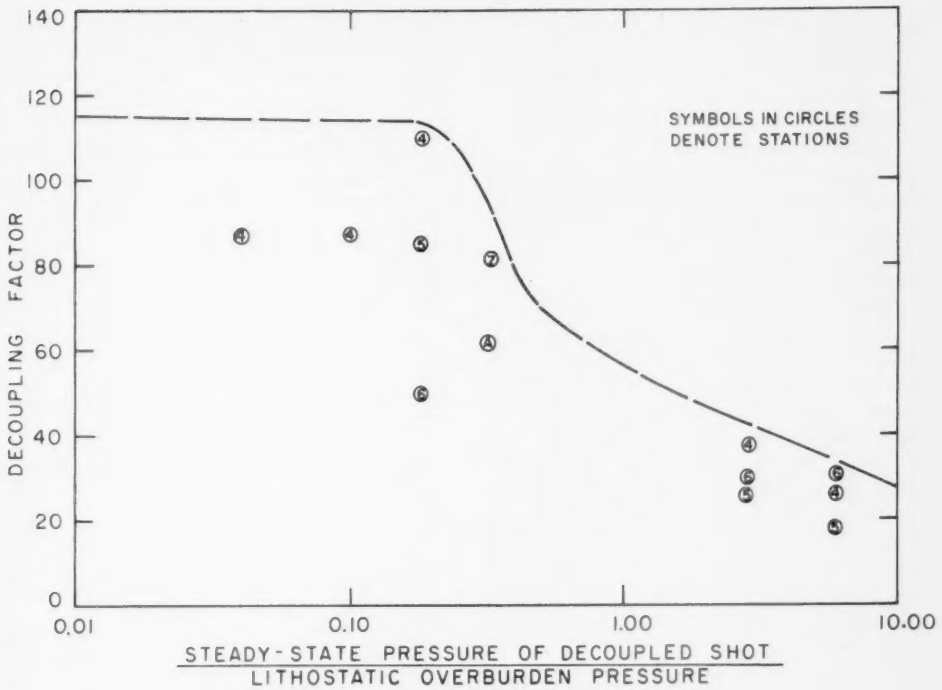

FIG. 33. Minimum decoupling factor at 30 to 40 cps.

20 to 2,000 lb can be decreased by *at least* 100, two orders of magnitude, if the shot is detonated in the center of a large spherical cavity deep in the earth.

When the volume is smaller than that required for optimum decoupling, there is still notable decoupling. For holes one-tenth the volume of that necessary for optimum decoupling, the propagated seismic energy is decreased by *at least* 10, one order of magnitude.

Decoupling is a function of frequency. This is indicated by the uniformity of analyses performed on each trace of six- or twelve-element arrays. However, the relationship is not definite. This is because the amplitude from an explosion for frequencies other than the dominant frequency is not sufficiently understood to be predictable.

The frequency-dependent decoupling factor derived in this report, including corrections for the higher-order terms and the effect of the spike, was not qualitatively confirmed for the frequency band 15 to 50 cps. Over this range the theory predicted a decrease of the decoupling factor with frequency of about 75 percent. Observed increases were from none to 100 percent. The theoretical prediction of the decoupling factor for the frequency band above 50 cps was not confirmed. Apparently, this was because the signals had no significant energy content in this higher-frequency band.

The difference in the dominant frequencies of the tamped shot and the decoupled shot in a particular shot pair was sometimes, but not always, discernible by visual inspection. It was not usually clear enough to distinguish between the two records. It was not evident in the Fourier spectra.

The occasional occurrence of an increase in decoupling at a frequency of 140 cps is not understood. It would amount to either a decrease at such frequencies for the decoupled shot or an increase at such frequencies for the tamped shot, or both. Although this phenomenon is not definite, lying as it does outside the flat bandpass of the *hf* recording system at about 6 db down, any future shots in the Winnfield area should instrument this

frequency band in an effort to clarify this problem.

This operation used long-period seismographs in the field, thus proving that it could be done. It is definitely feasible for the period of the seismometer equal to 15 seconds.

The power spectrum was found very useful for estimating the "smoothed" irregular Fourier spectrum. There is no theoretical justification for smoothing a spectrum, but it was desirable in the present study to discern trends.

While the decoupling results obtained in this study were from experiments in a low-yield range and over a relatively high frequency band, the agreement with theory is sufficiently good to suggest the general validity of the theory. There would appear to be no reason why corresponding results for nuclear explosions in the frequency range of interest for detection would not be obtained. Indeed, for a nuclear explosion, the impulse in the initial spike would be notably less than for the corresponding yield chemical explosion; hence, the limiting ratio of average cavity pressure to overburden pressure would be larger, at least $\frac{1}{3}$ and possibly 1.

However, this experiment has not definitely proved that decoupling of a nuclear explosion of 10 kt or greater is feasible or even possible. To demonstrate this, a set of nuclear explosions analogous to Project Cowboy will be necessary. It was not possible to use chemical explosions to create a pressure pulse on the wall of the cavity similar to that expected from a nuclear explosion. The pressure spike of a nuclear explosion may not directly affect the long-period seismic waves observed at distant seismic stations, but it may affect the rock about the cavity and so be indirectly significant. Using a gas mixture as the explosive source would probably simulate this feature of a nuclear explosion better than the high explosive actually used. In particular, the radiative transport of energy such as would occur in a nuclear explosion in an underground cavity might increase or decrease seismic coupling.

ACKNOWLEDGMENTS

The success of the surface seismic effort was due in great part to A. V. Shelton, Jr., and D. S. Carder. T. H. Pearce and W. V. Mickey expedited the field work. W. R. Mitchell and S. Sorkin supplied valuable background information and recommendations. J. E. Bush, F. F. Seifert, and D. B. Herbert provided excellent support and suggestions in the course of the experiment. R. G. Preston was responsible for the magnetic tape recorders being available. J. Whalen and P. Pomeroy gave special instruction and information on new instrumentation. Programming was by E. J. Gutnick and S. J. French, digitizing and data processing by F. O. Sullivan.

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REVIEW ARTICLES

RESOLUTION AND CURVED PATH COMPUTATION OF STEEP DIP USING AN ELECTRONIC COMPUTER*

DONALD R. OKSA†

A program for a basic IBM 650 electronic computer is discussed that resolves and computes four-way seismic dip control. The velocity parameters are a separate entry to the program in order that prospect re-evaluation, because of new velocity data, can be easily accomplished.

Ample identification of specific reflection data is permitted. Although written specifically for curved path velocity assumptions, modification for different types of velocity functions would be a comparatively simple task.

BASIC COMPUTATIONS

The basic computations (Figure 1) to the curved path method involve the values of initial velocity and acceleration. The value computed is the initial velocity divided by the acceleration, $(V_0)/(a)$. This value is computed only once for each set of velocity conditions and must be computed prior to the entry of the actual reflection data.

The computation of $e^{aT/2}$ is considered a basic computation. It is computed here because, if normal moveout computations are to be made, it is necessary to have this value. The necessary equations for normal moveout for a linear increase of velocity with depth function are available but have not been programmed at this time.

RESOLUTION

The resolution (Figure 1) of the seismic data into the direction of dip and the resolved delta t value involves approximately sixty percent of the program. Fortunately, resolution is independent of the velocity function which means that, with a minimum of re-programming, velocity functions other than the curved path method can be utilized.

The relationship of an apparent dip measure to the true dip usually is solved graphically, and a number of devices have been made to perform this operation. The graphical solutions use the tangent vector method. This method is admirably suited to seismic data since the "stepout time" or delta t values can be considered as a form of tangential measure the dip. The greater the angle of dip measured, the greater the delta t value recorded.

The mathematical solution of this same problem follows. Figure 2, a diagram showing the tangential relationship of apparent and true dip, shows the following:

1. The strike line AB in the horizontal plane ABC.
2. True dip θ and apparent dip ϕ.
3. $AC=FC$, $CD=CK=a$, $CE=GC=b$.
4. The angle $BAC=90°$.

Then,

$$\text{Tan } \theta = CD/AC, \tag{1}$$

$$\text{Tan } \phi = CD/BC = CE/FC = CE/AC, \tag{2}$$

$$\text{Tan } \phi/\tan \theta = b/a, \tag{3}$$

$$\text{Sin } \rho = AC/BC = \cos C, \tag{4}$$

$$AC/BC = \tan \phi/\tan \theta = b/a. \tag{5}$$

Therefore,

$$\text{Cos } C = AC/BC = b/a. \tag{6}$$

This can only be true if the angle CGK is 90 degrees. Figure 2 is not a representation of seismic ray paths. However, were the reflection points of the end traces at A and D, the delta t value would be a time measure of the elevation difference between the points A and D. The fore-

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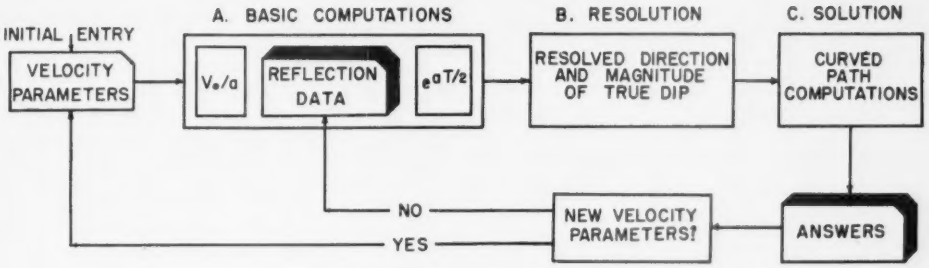

FIG. 1. Generalized computer flow chart.

going had one measure of the apparent dip and a strike line given. If two measures of apparent dip are made in such a manner that one of the measured points is common and the magnitude of the dip is measured over the same horizontal distance, it then becomes possible to determine both the magnitude of the true dip and the strike of the reflector. Figure 3 shows this condition where

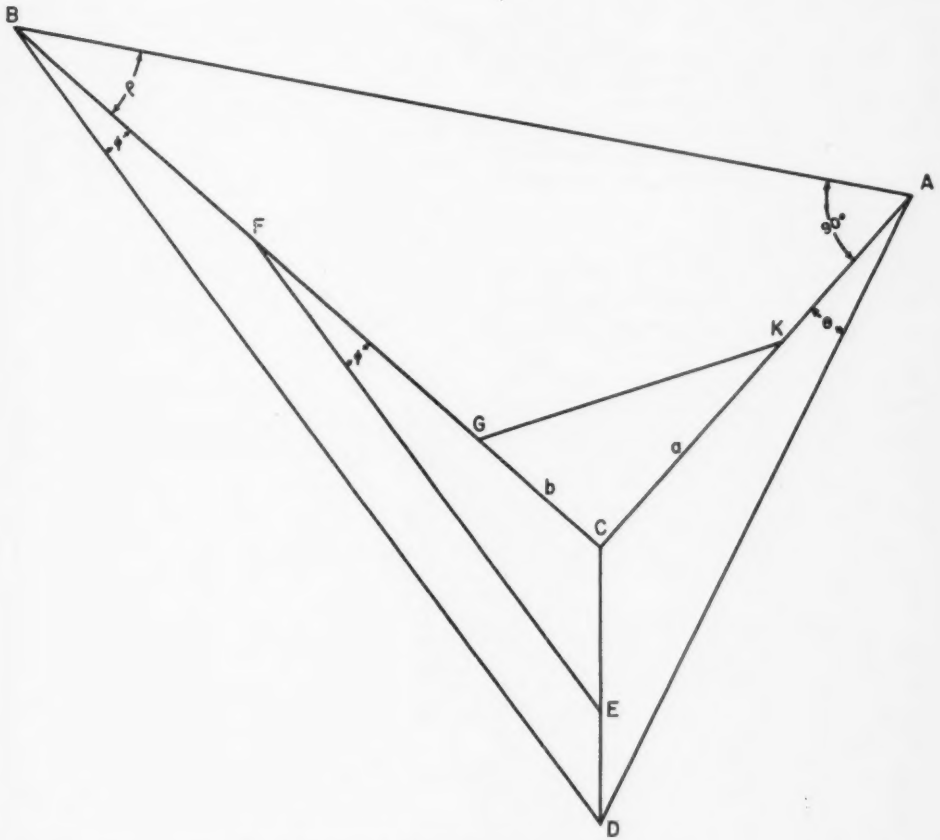

FIG. 2. Tangential relationship of apparent and true dip.

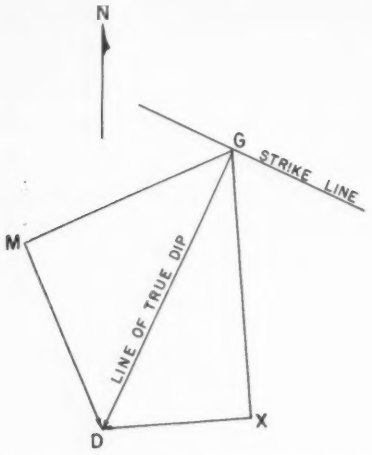

FIG. 3. Graphic resolution to determine true dip.

1. MD and DX are the tangents of apparent dip measures with perpendiculars erected to MD and DX at M and X; and
2. The intersection of these two perpendiculars is at point G. GD is the measure of the true dip and a perpendicular to GD will define a strike line.

It has been shown that the intersection of the perpendiculars of two concurrent apparent dip measures is a method of determining the magnitude of the true dip and the strike of the reflector. From analytic geometry the equation of a line, KH, through a specific point (X, Y) that is perpendicular to the line formed by this point and the origin of the Cartesian coordinates is

$$X \cos \alpha + Y \sin \alpha = P. \qquad (7)$$

P is the length of the line from the origin to the point (X, Y), and

The angle, alpha, is measured counterclockwise from the X axis.

Figure 4 illustrates these conditions.

The similarity of Figure 4 to Figure 3 exists to the extent that a substitution of DM for P could be made, and it would be possible to determine the angle, alpha, from the bearing of DM. Similarly, a second substitution could be made with DX as P and a second angle, alpha, determined. These substitutions would give the equations for lines MG and XG. Since the equations are simultaneous under the conditions of Figure 3, a unique point (X, Y) exists and is indicated as Point G in Figure 3.

Before substituting in equation (7) let it be recalled that the lengths of DM and DX were determined by the "stepout times," so the substitution of Δtm for DM and Δtx for DX is made where the subscripts of m and x designate the main and cross-spread measures of delta t.

Substituting in equation (7) and solving,

Coordinate Y

$$= \frac{[\Delta l_m \cos \alpha_x - \Delta l_x \cos \alpha_m]}{[\sin \alpha_m \cos \alpha_x - \sin \alpha_x \cos \alpha_m]} \qquad (8)$$

Coordinate X

$$= \frac{[\Delta l_m \sin \alpha_x - \Delta l_x \sin \alpha_m]}{[\sin \alpha_x \cos \alpha_m - \sin \alpha_m \cos \alpha_x]} \qquad (9)$$

$$\Delta l_R = [(\text{coord } X)^2 + (\text{coord } Y)^2]^{1/2} \qquad (10)$$

$$\tan \alpha_R = [\text{coordinate } Y]/[\text{coordinate } X]. \qquad (11)$$

In the second and fourth quadrants the angle, alpha$_R$, would be the bearing angle of Δl_R, and $(90-\alpha_R)$ would be the bearing angle of Δl_R in the first and third quadrants. The signs of coordinate X and coordinate Y will designate the quadrant of the true dip measure. This form of resolution permits the solution of any combination of delta t values or spreads at any angle less than 180 degrees to each other.

CURVED PATH SOLUTION

The previous resolution section gave the angle of bearing and the magnitude of the true

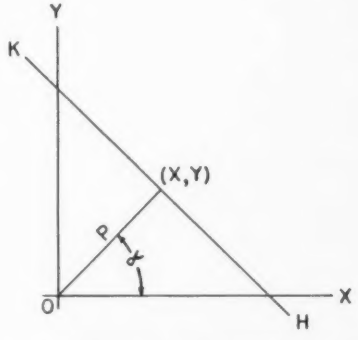

FIG. 4. Normal (KH) to line (P) through point (X, Y).

dip. The solution (Figure 1) for the offset X, the angle of dip in degrees, and depth Z can now be obtained by substitution in the following formulae (Oksa, 1958; Agocs, 1950, Kaufman, 1953):

$$\text{Sin}\,\theta_0 = [V_0\Delta t]/[\Delta X] \tag{12}$$

$$\text{Cos}\,\theta_0 = [1 - \sin^2\theta_0]^{1/2} \tag{13}$$

$$\tan\frac{\theta_0}{2} = [\sin\theta_0]/[1 + \cos\theta_0] \tag{14}$$

$$\tan\frac{\theta}{2} = \left[\tan\frac{\theta_0}{2}\right][e^{aT/2}], \tag{15}$$

$$\cos\theta = \left[1 - \tan^2\frac{\theta}{2}\right] \Big/ \left[1 + \tan^2\frac{\theta}{2}\right] \tag{16}$$

$$\sin\theta = [1 + \cos\theta]\left[\tan\frac{\theta}{2}\right] \tag{17}$$

$$\text{Depth } Z = [V_0/(a\sin\theta_0)][\sin\theta - \sin\theta_0] \tag{18}$$

If $\Delta t = 0$, Depth Z

$$= [V_0/a][e^{aT/2} - 1] \tag{19}$$

$$\text{Offset } X = [V_0/(a\sin\theta_0)][\cos\theta_0 - \cos\theta]. \tag{20}$$

Two other values also calculated are (a) Datum Z = Depth Z − datum plane and (b) Cotangent dip vector length.

The cotangent dip vector length is

$$\text{Vector length} = (\text{Cos}\,\theta/\text{Sin}\,\theta)(\text{Diff. Elevation}). \tag{21}$$

The foregoing are the equations the machine program solves. Exponentiation, sines and cosines, square roots, and tangents are solved in the computer by expansion series formulae. The program is written in SOAP II (Symbolic Optimum Assembly Program) form and requires a specially wired 533 panel for the computer. The output is printed with a 407 Bell output board.

Data are submitted for computation on the form illustrated in Figure 5. These data are keypunched onto IBM cards and verified.

The "velocity parameters" data are shown as

	INITIAL VELOCITY					ACCELERATION				VECTOR LENGTH FACTOR				
CN \ CC	6	7	8	9	10	17	18	19	20	27	28	29	30	80

CARD TYPE 1. VELOCITY DATA FORMAT

	IDENTIFICATION					TIME				DATUM				SPREAD BEARINGS MAIN SPREAD				CROSS SPREAD				Δt_M			ΔX_M				Δt_X			NEW VELT	ΔX_X			
CN \ CC	6	7	8	9	10	17	18	19	20	27	28	29	30	33	34	35	36	37	38	39	40	48	49	50	57	58	59	60	68	69	70	76	77	78	79	80

ALL UNUSED COLUMNS ZERO

CARD TYPE 2. REFLECTION DATA FORMAT

FIG. 5. Input data sheet.

SEISMIC GENERAL CASE
CURVED PATH

			INIT VEL	ACCEL	VECT		
	4						
	6		11000	280	5000		
IDEN T	6 TIME	BEARING	OFFSET	VECT	DIP	DEPTH	DATUM Z
021A 0	6 3188	N54E	10496	704	35	18770	18270
0300 0	6 1888	N02W	7788	454	48	8454	7954
0300 0	6 2080	N03E	133	1111	1111	11111	11111
0040 0	6 1125	N17W	1842	1617	17	6436	5936
	6		8850	630	5000		
031B 0	6 2080	S54W	9252	187	70	6595	5995
0260 0	6 1460	N16W	2387	1310	21	7763	7263
0251 0	6 1643	S15E	4897	593	40	7735	7235
40PH D	6 1304	N48E	4549	419	50	5012	4512
41HP D	6 1234	N37E	3650	582	41	5319	4819
	6		7100	750	5000		
041B H	6 1200	N68W	2876	583	41	4315	3815
042B X	6 1300	S88W	4624	139	75	2429	1929
043B H	6 1400	N81W	4268	348	55	4301	3801
043B V	6 1575	N81W	5040	308	58	4807	4307
	6						

FIG. 6. Computer program results.

Card Type 1 in Figure 5. Initial velocity and acceleration (as a three-decimal value) are self-explanatory. The vector length factor is simply the elevation difference, times ten, that one wishes the cotangent dip vector to represent on the maps.

The reflection data are entered according to the Card Type 2 format of Figure 5. Each entry is appropriately labeled. Spread bearings are entered only to the nearest degree, such as N30E. Delta t values and the symmetrical spread length are entered under the subscripted notation for each as M for the main spread and X for cross-spread values. A zero in Column 76 under "New Vel.?" indicates to the computer than no velocity change is made. Any value other than zero indicates to the computer that new velocity conditions are being entered, hence the program is initiated properly for this condition.

Figure 6 is an example of the printout of the answers of the program. The first velocity data and the first answers are labeled. Subsequent changes in velocities just print, but are obvious. The unlabeled four and series of 6's are control data for the 407 Bell Printout Board. These and no labels at velocity change points are concessions which are made to the computer installation for ease in handling of data processing.

The program accounts for impossible conditions where $\sin\theta_0$ exceeds 1. The third line of answers illustrates this. The identification and reflection time are recorded. The correct bearing of the resolution prints out. Under the offset column, however, is recorded the resolved delta t value. The remaining answers are not computable, and this is indicated by a series of ones.

CONCLUSIONS

The electronic computer program for resolving and computing seismic reflection data can be a valuable tool to aid in interpretation. Comparative computing times by three methods for 150 reflections are these.

Wave-Front Chart Single Function	Desk Calculator 10 Different Functions	650 Program 10 Different Functions
2 hours Resolution 2½ hours Chart Lookup	2 hours Resolution 50 hours Calculating	17 min. Keypunch and verify 3 min. Computing 1 min. Listing 2 min. Setup Time
4½ hours	52 hours	23 minutes

The above table is for a single calculation for each reflection. In a re-evaluation because of a changed velocity the times would be 2½ hours for chart lookup, 50 hours by a desk calculator, and about 7 minutes with the computer program. The ease of re-evaluation can thus be easily seen and appreciated. Empirical velocity functions can also be determined much more rapidly because of the simplicity of changing velocity parameters.

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Oksa, D. R., 1958, An empirical velocity determination in southern Oklahoma: Geophysics, v. 23, pp. 823–837.

GEOPHYSICS, VOL. XXVI, NO. 6 (NOVEMBER, 1961), PP. 806-819, 6 FIGS.

THE RECIPROCAL METHOD OF ROUTINE SHALLOW SEISMIC REFRACTION INVESTIGATIONS*

L. V. HAWKINS†

The Reciprocal Method of shallow seismic refraction investigation provides a simple reliable method for surveys where the absolute depths to important refractors and an analysis of the velocities in the refractors are required in detail. The depth computation is based on an early (1931) concept, termed here the time-depth, which differs slightly from the delay-time. The calculation of the individual time-depths and of the corrected travel times within the refractor require only simple numerical computation. Hence, the method is very suitable for routine survey procedures in which use is made of composite velocity terms for multilayered overburdens. The basis and procedures of the Reciprocal Method are presented together with examples illustrating the application of the method and the technique of velocity analysis.

INTRODUCTION

All seismic shallow refraction methods are based on the recording of the first arrival travel times of elastic waves and there is a close similarity between the methods which aim at extracting detailed information from the observed results. However, such methods differ in the nature of the approximations made, in the field and computational procedures used, and in the relative or absolute nature of the results obtained. The purpose of this paper is to restate one of the very early detailed methods and show how it has been developed into a simple reliable method which is suitable for routine survey procedures.

The Reciprocal Method employs a standard in line arrangement of geophones and shotpoints with pairs of corresponding shotpoints bracketing the geophone spread. However, in addition to the travel times along the geophone spread, the travel time between each pair of corresponding shotpoints is also recorded and is termed the reciprocal time. The method used for depth determination is based on that of Edge and Laby (1931), and the method of refractor velocity analysis makes use of the time-depth terms calculated for the geophone stations.

The Reciprocal Method is used by the Bureau of Mineral Resources of the Department of National Development, Australia, and has been developed to its present form by the author together with other members of the engineering group of the Bureau, in particular Mr. W. A. Wiebenga and Mr. D. F. Dyson. The method described here was used as a standard survey procedure by the author in a group of surveys at Canberra, Australia, in 1956 (Hawkins, 1957). An earlier and partial form of the method has been described by Urquhart (1956).

In the description of the method it is assumed that the reader is familiar with the nature of elastic waves and with the fundamental principles of elastic wave propagation. Also, the velocity of vertically travelling waves within each recorded layer is taken as constant. Departures from this assumption are considered in the section on errors.

DETERMINATION OF DEPTHS TO REFRACTORS

The Time-depth

The determination of depths to refractors in the Reciprocal Method is based on what may be termed the "time-depth." The time-depth to a refractor is the time delay associated with the critical ray in travelling between the refractor and the surface and is defined as follows:

The time-depth to a refractor is equal to the travel time for the segment of the critical ray path between the refractor and the surface minus the time required to travel the projection of the above

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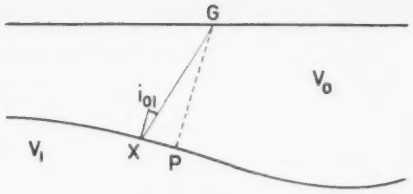

FIG. 1. Ray path in definition of time-depth.

segment on the plane of the refractor at the velocity of the refractor.

In the two layer case shown in Figure 1, the time-depth to the refractor at the point G, t_G, is

$$t_G = (GX/V_0 - PX/V_1) \qquad (1)$$

where V_0 and V_1 are the seismic velocities of the surface layer and the underlying refractor, respectively. Equation 1 may be readily reduced to the expression,

$$t_G = Z_G \cdot \text{Cos } i_{01}/V_0,$$

and rewritten in the form,

$$Z_G = t_G \cdot V_0/\text{Cos } i_{01}, \qquad (2)$$

where Z_G is the distance from G to the refractor along the normal to the plane of the refractor and i_{01} is the critical angle between the two velocities V_0 and V_1. Hereafter, the distance Z_G will be referred to as the depth.

It is apparent that the time-depth to a refractor closely resembles the "delay time" to the refractor as defined by Nettleton (1940). However, the assumed horizontal disposition of the refractor which is inherent in the definition of the delay-time is no longer necessary since the depth Z_G is taken normal to the plane of the refractor. The time-depth is equivalent to a half-intercept time but does not include the inherent ambiguity of the intercept time since it is affected only by the conditions under the geophone station.

Calculation of the Time-depth

Where a geophone spread is bracketed by shotpoints such that all recorded travel times are of critical rays from the same refractor, the time-depths may be calculated by following the procedure of Edge and Laby (1931, p. 339; Heiland, 1940, p. 548–549). The time-depth at a geophone station is obtained by adding together the travel times from both shotpoints to the geophone station, subtracting the shotpoint-to-shotpoint travel time (the reciprical time), and halving the result.

Thus, in Figure 2, the time-depth t_G at the geophone station G is

$$t_G = \tfrac{1}{2}(t_{S'G} + t_{S''G} - t_{S'S''}) \qquad (3)$$

where $t_{S'G}$, $t_{S''G}$, and $t_{S'S''}$ are the travel times of the critical rays from S' to G, S'' to G, and S' to S'', respectively.

By writing the above travel times in terms of their segment travel times as distance/velocity, equation 3 may be reduced to

$$t_G = \tfrac{1}{2}(GX/V_0 + GY/V_0 - XY/V_1).$$

Further, if the refractor is assumed to be plane between the points X and Y, then from the symmetry,

$$t_G = (GX/V_0 - PX/V_1)$$

which is the expression for the time-depth and reduces as before to equation 2.

The Depth Conversion Factor

The term $V_0/\text{Cos } i_{01}$ in equation 2 may be regarded as a "depth conversion factor" for the two-layer case. The general form of the depth conversion factor for a refractor of velocity V_n, which is overlain by a layer of velocity V_m giving a critical angle i_{mn}, is $V_m/\text{Cos } i_{mn}$. This may be determined directly from the nomogram shown in Figure 3 if the velocities V_m and V_n are known.

The depth conversion factor is a velocity term and also may be written in the form $V_mV_n/(V_n^2 - V_m^2)^{1/2}$. The divisor Cos i_{mn} may be regarded as a correction for the inclination of the ray path through the layer overlying the refractor. This inclination is relative to the normal to the refractor and is controlled by the velocity contrast between the layer and the refractor as expressed in Snell's Law.

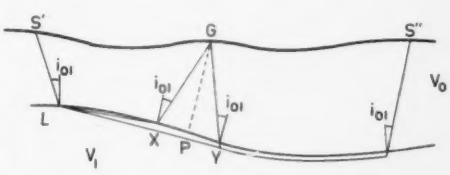

FIG. 2. Ray paths in calculation of time-depth.

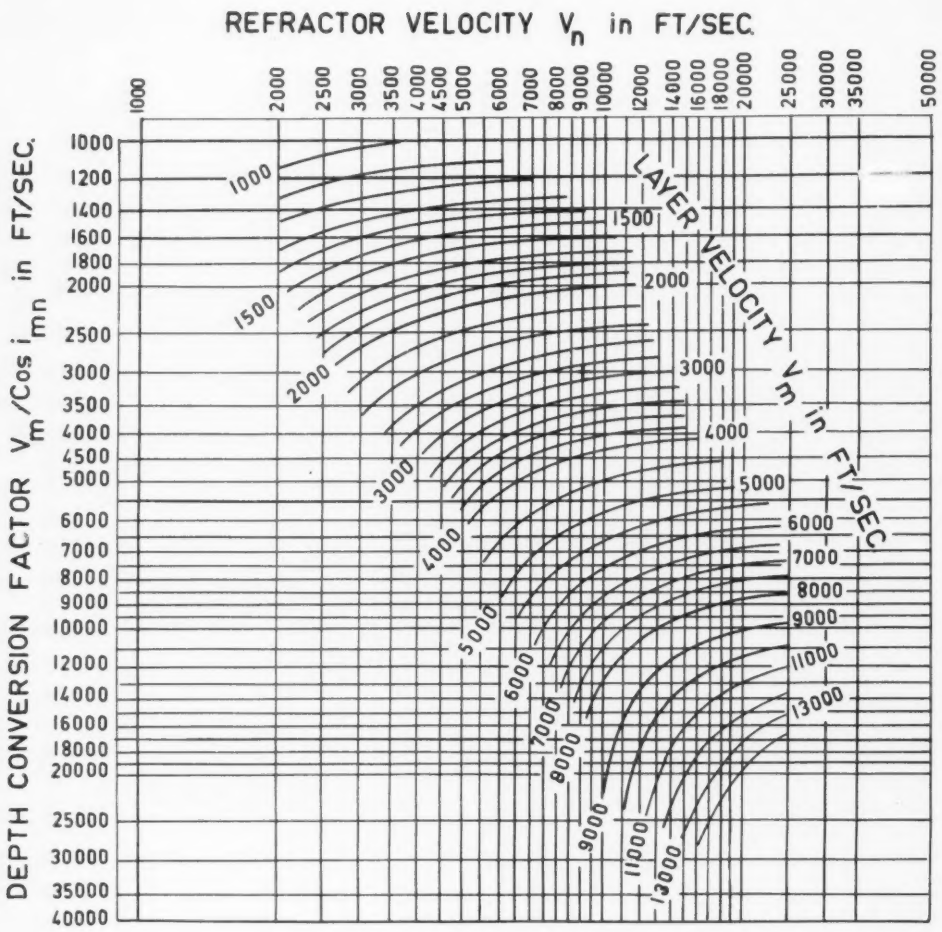

FIG. 3. Nomogram of depth conversion factor for layer of velocity V_m and underlying refractor of velocity V_n.

Where a refractor of velocity V_n is overlain by two or more layers of different velocity, the velocity term $V_m/\text{Cos}\ i_{mn}$ will vary for each layer as the layer velocity V_m varies. This is due to both the different layer velocity and the different inclination of the ray path. Consequently, either the thickness of each layer must be determined separately in a manner similar to intercept time determinations, or a composite depth conversion factor must be calculated for the refractor. The method adopted will depend on the detail required from the survey.

Where the depths to all recorded refractors are required at all geophone stations, the time-depths for each refractor must be computed at each geophone station. The computation then follows the procedure of determining the thickness of each successive layer from the time-depth of the immediately underlying refracting layer and is identical to that for half-intercept time computations. For this purpose it is assumed that the interfaces are parallel in the region below the geophone station.

In the general form, the equation for determining the thickness of the mth layer, Z_m, from the time-depth (or half-intercept time) t_n to the

immediately underlying nth layer refractor is

$$Z_m = \left(t_n - \sum_{a=0}^{m-1} Z_a \cdot \operatorname{Cos} i_{an}/V_a\right) \cdot V_m/\operatorname{Cos} i_{mn} \quad (4)$$

where the term,

$$\sum_{a=0}^{m-1} Z_a \cdot \operatorname{Cos} i_{an}/V_a,$$

represents the sum of the "time-thicknesses" of all the layers overlying the mth layer; the time-thickness of a layer being the time delay through that layer for the critical ray from the refractor. Hence, the bracketed terms represent the time-thickness of the mth layer. This is multiplied by the simple depth conversion factor between the V_m and V_n velocities to yield the thickness of the mth layer. Equation 4 may be solved by use of the nomogram in Figure 3 and the values of Z_0, $Z_1 \cdots Z_{m-1}$ which have been previously determined in a similar manner.

Where only the depth to a particular, important refractor is required at all geophone stations, the thicknesses of the layers overlying the important refractor are determined mainly for evaluating the composite depth conversion factor for the important refractor. These thicknesses are determined as above from the half-intercept times of shotpoints in or near normal geophone spreads and from special "weathering spreads." The weathering spreads have a short geophone interval and give more detailed information on the near surface layers.

Where such thicknesses are determined, the composite depth conversion factor may be calculated by summing the thicknesses (Z_a) to obtain the depth of the important refractor and dividing this depth by the time-depth or half-intercept time to the important refractor (t_n). Thus, the composite depth conversion factor, $\overline{V}$, to an nth layer refractor is

$$\overline{V} = \sum_{a=0}^{n-1} Z_a/t_n. \quad (5)$$

In this manner, the composite depth conversion factor is determined at regular intervals along the traverse and interpolated at each geophone station.

The depth to the important refractor at a geophone station G, Z_G, is calculated from the equation,

$$Z_G = t_G \cdot \overline{V}_G \quad (6)$$

where t_G is the time-depth to the important refractor (i.e. the value of t_n at G) and $\overline{V}_G$ is the corresponding composite depth conversion factor.

ANALYSIS OF VELOCITIES IN REFRACTORS

The slope of the time-distance curve beyond the critical distance determines the apparent velocity of seismic waves in the refractor in the direction of shooting along the traverse. In the classical method the apparent velocities from opposite directions are used to determine the true velocity in the refractor. Where the refractor depth and/or the velocity distribution in the material overlying the refractor are irregular, the plotted time-distance curve will scatter about the line of the apparent velocity of the refractor. Here, the apparent velocities may still be determined by drawing lines of best fit to the scattered points. However, this will obscure rapid variations of the refractor velocity which may be of considerable importance, particularly in surveys for the investigation of foundation conditions.

Use of the Time-depth

By the simple procedure of subtracting the time-depths from the recorded travel times at geophone stations, the effect of any irregularities both in the refractor depth and in the velocity distribution in the material overlying the refractor is removed.

This may be illustrated with the two-layer case shown in Figure 2. The corrected travel time from the shotpoint S' for the geophone station at G, $t'_{S'G}$, is

$$t'_{S'G} = t_{S'G} - t_G \quad (7)$$

where $t_{S'G}$ is the recorded travel time and t_G the time-depth. By use of segment travel times and the definition of the time-depth, this equation reduces to

$$t'_{S'G} = S'L/V_0 + LP/V_1 \quad (7a)$$

which is the travel time from the shotpoint S' to the point P on the refractor from which the normal to the refractor passes through the geophone placing at G. As before, the travel times and the

time-depths must be from the same refractor.

Since the corrected travel times refer to points on the refractor from which the normals pass through the geophone placings, the corrected time-distance curves are plotted after the depth profile of the refractor has been constructed. The slope of the corrected curves should be the same for both directions of shooting, and the true velocities in the refractor may be determined directly from the slope of the curves.

The velocities are measured parallel to the refracting interface and in the direction of the traverse and, of course, may vary with direction for anisotropic rocks. Also, a small transition zone will occur above a velocity change in the refractor due to differences in the inclination of the ray paths above the refractor. The width of the transition zone will depend on the horizontal displacements between the recording geophone and the points at which the recorded rays leave the refractor.

For the overlying less important refractors for which time-depths have not been calculated, the velocities in the refractors may be determined in the classical manner, using the apparent velocities from reverse shooting. A sufficiently close approximation to these velocities may usually be obtained from the equation,

$$V_m = 2 \cdot V_{m'} \cdot V_{m''}/(V_{m'} + V_{m''}) \text{ (approximately)}, \quad (8)$$

(Heiland, 1940, p. 523) in which V_m is the true velocity and $V_{m'}$ and $V_{m''}$ the apparent velocities in the refractor from reverse shooting.

CORRECTIONS

A shot correction is required since a surface to surface subtractor (the reciprocal time) is used in the calculation of the time-depth. The shot correction in effect places the shot at the surface of the ground and is approximately equal to the ratio D_s/V_s where D_s is the distance of the shot from the surface and V_s is the velocity in the material between the shot and the surface. The correction is positive for buried shots, negative for air shots, and is applied during the reading of the records.

Elevation and weathering corrections are generally unnecessary since the topographic surface is taken as the datum and the weathered or surface layer is treated as a layer in the multi-layered problem. However, if a differential displacement of some of the travel time irregularities is apparent with reverse shooting, it may be possible to distinguish between variations in the thickness of surface and intermediate layers and apply a standard correction procedure for the surface layer. This follows from considerations of the inclination of the ray paths and the horizontal displacement between the recording geophone and the points at which the recorded rays leave the refractor.

ROUTINE SURVEY PROCEDURE

In most problems for investigation, it is possible to select from the refractors present one important refractor. This refractor is generally overlain by several layers of differing seismic velocity. Such investigations are suitable for a basic or routine survey procedure in which use is made of composite velocity terms but which may be modified as required.

Ambiguities Concerning the Important Refractor

The routine survey procedure must yield time-depths to the important refractor at all geophone stations. Hence, the travel times used in the time-depth calculation must be shown to be of critical rays from the important refractor. This may be done by resolving ambiguities in the time-distance curve prior to commencing computations.

The ambiguities which must be resolved occur when there is a change in slope of the time-distance curve showing an increase in apparent velocity with an increase in distance from the shotpoint. Such a change in slope may be caused either by a change in the dip and/or the velocity in the same refractor, or by the recording of a deeper, higher velocity refractor.

Reverse shooting, which is necessary from other considerations, does not resolve this ambiguity when the change in slope occurs in a similar position from both directions of shooting. However, from considerations of critical distance this may be simply resolved by recording from two shotpoint-to-spread distances for each direction. The point of change of slope in the time-distance curve will be displaced towards the more distant shotpoint if a deeper, higher velocity refractor has been recorded; but no displacement will occur with a change of dip or velocity in the same refractor. The differentiation between a dip or a velocity change in the refractor presents no

difficulties and is resolved in the method itself. A comparison between the slopes of the time-distance curves for the shots from the same direction is rapidly effected with a parallel rule using two large set-squares.

By this procedure it is readily apparent which geophones have recorded the critical rays from the important refractor. To show that the reciprocal time is also of a critical ray from the same refractor, this travel time is checked against continuous travel time profiles which are obtained by tying adjacent spreads by means of one or two common geophones. The time-depths to the important refractor are then calculated from the travel times of the more distant shotpoints and are checked against those calculated from the closer shotpoints where the important refractor has been recorded. This serves as a further check on the reciprocal times as well as the individual travel times.

In most shallow investigations the important refractor has a relatively high velocity and can be recorded over the distance of the spread and the reciprocal geophone without difficulty. However, if the refractor can be recorded over only part of this distance, additional shotpoints will have to be used. If necessary, the reciprocal times can be determined from the continuous travel time profiles.

The Composite Depth Conversion Factor

The velocities and half-intercept times or time-depths of the near surface and intermediate layers are obtained at the special weathering spreads which are recorded at the alternate junctions of normal spreads on a continuous traverse. Further, without losing the above resultion of ambiguities in the time-distance curves of the normal spreads, it is usually possible to record from the intermediate layers with the first few geophones near the closer shotpoints. Thus, intercept times and apparent velocities for the intermediate layers are obtained near the ends of the normal spreads. Additional values are obtained from a fifth shotpoint placed at the center of the normal spreads.

Hence, the composite depth conversion factor is calculated at the locations of the weathering spreads. The lateral variation of this factor is controlled by similar calculations for the shotpoints near the ends and within the normal spreads. The depth to the important refractor at each geophone station is computed by multiplying the calculated time-depth by the corresponding composite depth conversion factor.

Field Practice

For continuous profiling, the recording equipment is placed near the junction of two normal spreads which are tied by one or two common geophones. Each normal spread is recorded using the above five-shot pattern unless more shotpoints are required to record fully the important refractor. A weathering spread is also recorded. The equipment is then moved two spread lengths along the traverse, and the procedure repeated.

For the weathering spreads, a geophone interval of 10 ft is used with shotpoints recorded from distances of 10 ft and successively increasing distances which give an adequate shotpoint-to-geophone overlap. Usually, a total of six or eight shotpoints are required. A separate geophone cable with the appropriate takeouts is used.

The geophone interval used for the normal spreads will depend on the detail required by the problem, but for most problems an interval of about 40 or 50 ft has been found suitable. With an interval of 40 ft, conventional equipment of twelve channels (of which one is used for the reciprocal geophone) yields a spread length of four hundred feet. Weathering spreads occur every eight hundred feet along the traverse and close shotpoints every two hundred feet.

The shots are usually placed in auger holes at a depth of a few feet, but may be placed deeper in well populated areas. The cables used as shot firing lines are also used to transmit the signal from the reciprical geophone. When geophones are placed near previous shotpoints, care is taken to plant the geophone away from the disturbed zone of the shot. In general the shotpoint is located a little to one side of the traverse and the geophone to the opposite side.

Reduction Procedure

The recorded travel times of each spread are plotted as time-distance curves, and the lines of best fit drawn for the apparent velocities. A comparison of the time-distance curves for the reverse directions and a direct comparison for the two shotpoint-to-spread distances for each direction are made. The reciprocal time is checked against the extended travel time profile. The time-depths to the important refractor are then

computed on tabulated result sheets, and the recorded travel times corrected by the subtraction of the corresponding time-depths.

The composite depth conversion factor is evaluated along the traverse and the depths to the important refractor computed. The depths are plotted on vertical sections along traverse lines by striking arcs of scaled radius beneath each geophone station, and the refractor profile is drawn in. The new time-distance curves are then plotted, the true refractor velocities determined and indicated on the section. The known thicknesses and velocities of the overlying layers are also indicated. It is important to note that initial reductions should be carried out during the time of the field survey to ensure that satisfactory results are obtained in the field.

ERRORS

Errors in Depth Determinations

The results of a survey should be accompanied by a statement of the expected errors in the depth determinations. Where sufficient empirical control is available from the results of check drilling, the expected errors may be calculated by establishing a direct correlation between the seismic and drilling results. The mean error in the seismic depth determinations may be taken as an estimate of any bias in the seismic results and the standard deviation from the mean taken as the equivalent random error in the seismic results. By way of example, the six drill-holes shown in Table 1 for the Commonwealth Avenue bridge site are all within 20 ft of geophone stations. The calculation of errors reveals a zero mean error indicating the results are without bias. The equivalent random error indicated by the standard deviation from the mean is plus or minus nine percent. This represents a typical example of the errors obtained for check drilled surveys.

If empirical control is absent or insufficient, a qualified statement on the errors expected under similar survey conditions may be given as a guide to those reading the survey report. The error estimate will be based on experience and on considerations of the sources of possible error in both the time term and the velocity term of the depth computation.

Errors in the time term may result from reading errors and from a smoothing of the profile of an irregular refractor which is inherent in both the recorded travel times and in the calculation of the time-depth. Further errors may result from the recorded rays following minimum time and not necessarily critical ray paths. This leads to errors from variations in the travel paths through the refracting layer for the rays recorded by the various spread and the reciprocal geophones. The variations in travel paths result from either an increase in refractor velocity with depth or a raised irregularity in the refractor profile under a spread geophone.

Errors in the velocity term may result from the discrete and not continuous sampling of both the time-distance curve and the calculated velocity term along the traverse. In the case of the surface velocity continuously increasing with depth, the velocity distribution is approximated with a number of discrete velocity layers. Further errors may result from the inability of the refraction method to detect velocity inversions, layering within a blind-zone above a refractor, or velocities in directions other than parallel to a refract-

Table I. Comparison of Measured Seismic Velocities with the Type and Condition of the Bedrock Refractor

Drill-hole	Dept in ft	Location	Type and Condition of Bedrock	Seismic Velocity in ft/sec
5	188	10 ft from stn. A840	Soft decomposed shale or mudstone.	6,500
1	80	Stn. A160	Weathered mudstone with pockets of soft decomposed mudstone.	6,500
3	90	Stn. A640	Weathered mudstone (less weathered than in hole 1) with pockets of soft decomposed mudstone.	7,200
6	82	Stn. C00 (not shown)	Broken, partly weathered siltstone.	8,000
2	75	Stn. A400	Partly weathered mudstone with appreciable strength.	9,500
4	60	20 ft from stns. A760 and A720	Partly weathered mudstone with appreciable strength.	9,500

ing interface. Such errors may readily introduce a bias into the calculated depths.

From considerations of the magnitude of possible errors in the depth computation, it appears that the greatest uncertainties are present in the determination of the velocity through the material overlying the refractor. However, the availability of drillholes at the time of the survey for both vertical velocity measurements and direct correlation will minimize the possible errors from the deficiencies in the refraction method.

For surveys under "normal" conditions and without drilling control, the errors usually expected may reasonably be stated as having an equivalent random error within ± 10 to 15 percent with a possible bias within 10 percent of the calculated depths. This estimate would be applied to the example survey of the Acton weir site.

Errors in Velocity Determinations

Errors in the measured velocities are due to the time errors and to distance errors which occur in the plotting of the corrected time-distance curves. The transition zones in the velocity profile, which occur above velocity changes in the refractor, must also be considered. However, where the velocity in the refractor is constant over more than three geophone stations, the measured velocity should be determined with good accuracy.

COMMENTS

Seismic refraction methods which aim to extract detailed information on the refractor profile are the graphical methods of Thornburgh (1930, p. 185–200) and others, and the analytical methods based on isolating time terms at geophone stations. The graphical methods of Thornburgh involve less assumptions than the analytical methods and should therefore obtain a higher accuracy. However, the main uncertainties still remain in the determination of the velocity distribution in the material overlying the refractor. In view of the additional time involved in the construction of wave-front diagrams, it is only in the exceptional cases where the analytical approximations are unacceptable that the graphical methods may be used with real advantage. Such cases arise where deep, irregular refractors with steep dips and low velocity contrasts with the overlying material are present.

The analytical methods of isolating the time term at geophone stations are based on the concept of either the time-depth or the delay-time. The assumptions and procedures used differ in each case, but the accuracy of the results obtained, appear comparable.

For the time-depth, the refractor is assumed to be plane in the limited region below the geophone station between the points from which the recorded rays leave the refractor. This follows from the calculation of the mean value of the time-depths from opposite directions of shooting. No additional assumptions are made for the dip of or the velocity in the refractor. Critical ray paths are assumed for both the time-depth and the delay-time.

For the delay-time, the refractor is assumed to be horizontal at the points where the recorded rays leave the refractor. Also, the velocity in the refractor is assumed to be constant. However, if changes in the refractor velocity extend over a considerable distance, they are readily corrected in the calculation of the delay-time differences.

In the determination of the delay-time differences, the delay-time curves are migrated towards their respective shotpoints by the approximate horizontal displacement between the recording geophone and the points at which the critical rays leave the refractor. This procedure reduces the errors from the slight smoothing inherent in the calculation of the time-depth. However, additional errors introduced due to variations in elevation and surface conditions between the recording and the migrated position offset the advantage from this procedure.

In the reduction of results, the time-depths have the advantage of involving only simple numerical computation and yield the absolute depth profile of the refractor directly. Delay-time analysis usually involves a somewhat more lengthy procedure with a number of graphical steps. This yields a relative delay-time profile which may be tied to half-intercept times to obtain the absolute depth profile of the refractor.

The use of the time-depth in the analysis of the refractor velocity is related to a method sometimes used in seismic reflection surveys as a check on the geophone placing and on serious errors in the measured subweathering velocity along the geophone spread (Vale, 1957). In this method, if G' and G'' are two successive geophone stations which record from shotpoints S' and S'' on respective ends of the geophone spread, the recorded travel times are grouped as

($t_{S'G''} - t_{S'G'}$) and ($t_{S''G'} - t_{S''G''}$). The Mean of the Sum of these groups yields the approximate travel time in the refractor between the geophone stations. The Mean of the Difference of the groups yields the delay-time difference between the two stations.

Finally, the Plus-Minus method of Hagedoorn (1959, p. 158–182) may be seen to be basically similar to the Reciprocal Method. Hagedoorn's Plus values are identical to the time-depths, and his Minus values give a refractor velocity analysis in a similar manner to the Mean Sum method.

EXAMPLES

Two examples are included. The first is an example of a completed survey of a weir site at Acton, Canberra, Australia. The second is a specific example illustrating the technique of velocity analysis for a seismic traverse of the Commonwealth Avenue bridge site, Canberra, chosen because of subsequent check drilling of the refractor velocities.

Both surveys were carried out in June, 1956, for the Department of Works, Canberra, by a geophysical party of the Bureau of Mineral Resources, Melbourne, Australia. The geophysical party consisted of the author as party leader-geophysicist, an observer-shooter, and an assisting geophysicist for some of the time. Two to four field hands were supplied by the Department of Works. The surveys were two of a group of nine surveys of dam, weir, bridge, building, and quarry sites carried out between May and August, 1956. As both surveys were conducted in partly populated areas which had considerable traffic, shots were placed in auger holes at a depth of 5 to 10 ft to reduce noise and damage.

Example of a Completed Survey—the Acton Weir Site

The Acton weir site, which has since been abandoned for a more favorable alternative site, formed part of the Canberra Lakes Scheme. The site extended over much of the Royal Canberra golf course and lies across the Molonglo River at Acton, Canberra.

Geology.—The geology of the site is rather complex and is covered by undifferentiated Recent to Pleistocene deposits almost entirely. The main structural feature of the area is the Acton fault which was known to occur somewhere on or near the site. The Acton fault is a major normal fault which strikes north-west and separates folded Ordovician sandstones and shales to the south-west from folded Silurian calcareous shales with limestone bands, shales, sandstones, tuffs, and rhyolites to the north-east (Opik, 1953).

Seismic Results.—The location of the seismic traverses together with the topographic and "unweathered bedrock" contours, zones of low seismic velocity in the bedrock, and possible fault zones are shown in Figure 4. Cross-sections along traverse lines showing the depth profiles of the "weathered bedrock" and the "unweathered bedrock," the measured seismic velocities in the bedrock, and average velocities through the overburden are shown in Figure 5.

In the presentation of the seismic results, a surface layer of 1,200 ft/sec velocity and an underlying layer of 5,000 ft/sec velocity have been grouped together as overburden, and an average velocity calculated for it which ranges between 1,350 and 1,900 ft/sec. This layer ranges between 12 and 47 ft in thickness and is composed mainly of alluvial deposits.

Beneath the overburden is a layer which ranges in velocity from 5,500 to 9,500 ft/sec except at one place on traverse *M* where the velocity is about 12,000 ft/sec. The thickness of this layer varies considerably throughout the area. On the western half of the site the thickness is between 39 and 115 ft, averaging 73 ft. On the eastern half of the site it is much thinner and has been detected at only a limited number of places where it is between 10 and 50 ft in thickness and has a velocity of about 9,000 ft/sec. The general term, "weathered bedrock," is used to denote this layer.

Underlying the "weathered bedrock" layer is a refractor of increased velocity which ranges from 8,000 to 20,000 ft/sec. The low velocities from 8,000 to 9,000 ft/sec are interpreted as occurring in zones of fracturing and partial weathering. Faulting is postulated as the cause. These zones correspond with relatively lower velocities in the overlying "weathered bedrock" layer. The remaining velocities are in the range of relatively unweathered sedimentary rocks, and this refractor is denoted in general terms as the "unweathered bedrock." The use of the above general terms is considered justified because the implications as to the state of the rock is in general correct, although some exceptions occur.

From considerations of the geology it appears that the higher velocities in the "unweathered

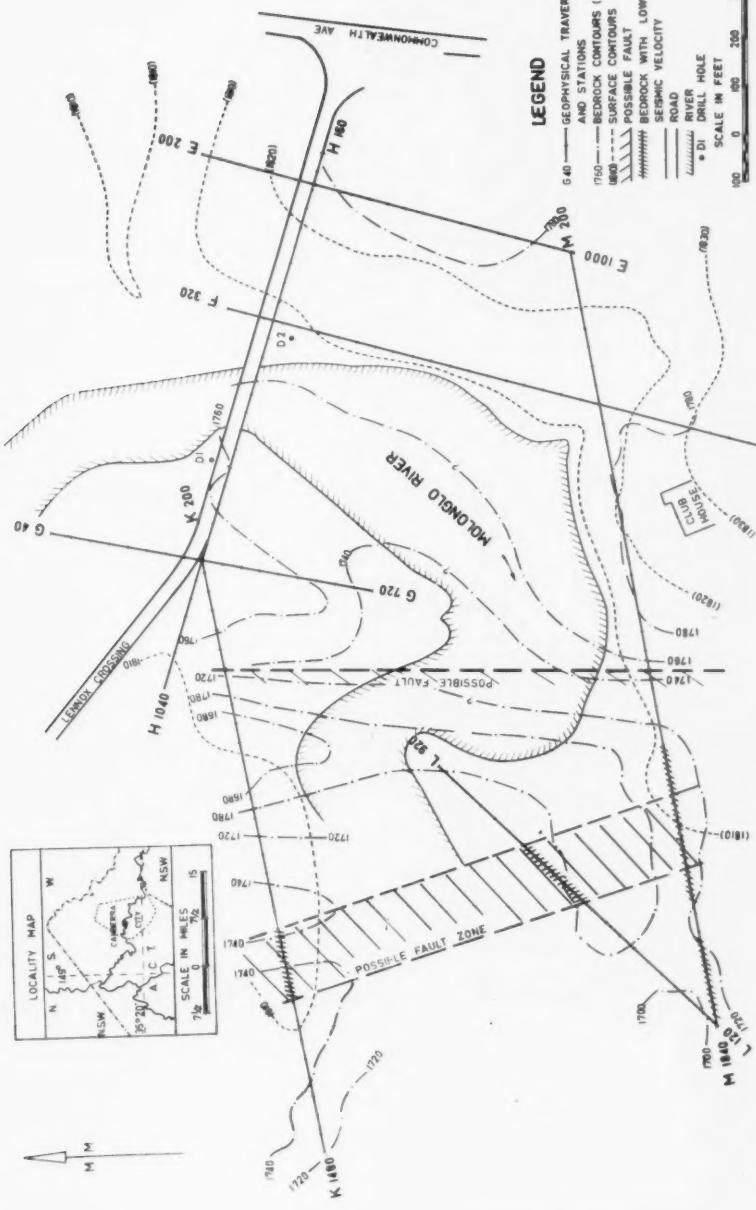

FIG. 4. Traverse plan of survey of Acton weir site showing unweathered bedrock contours and possible fault zones indicated by seismic results, surface contours, and drill locations.

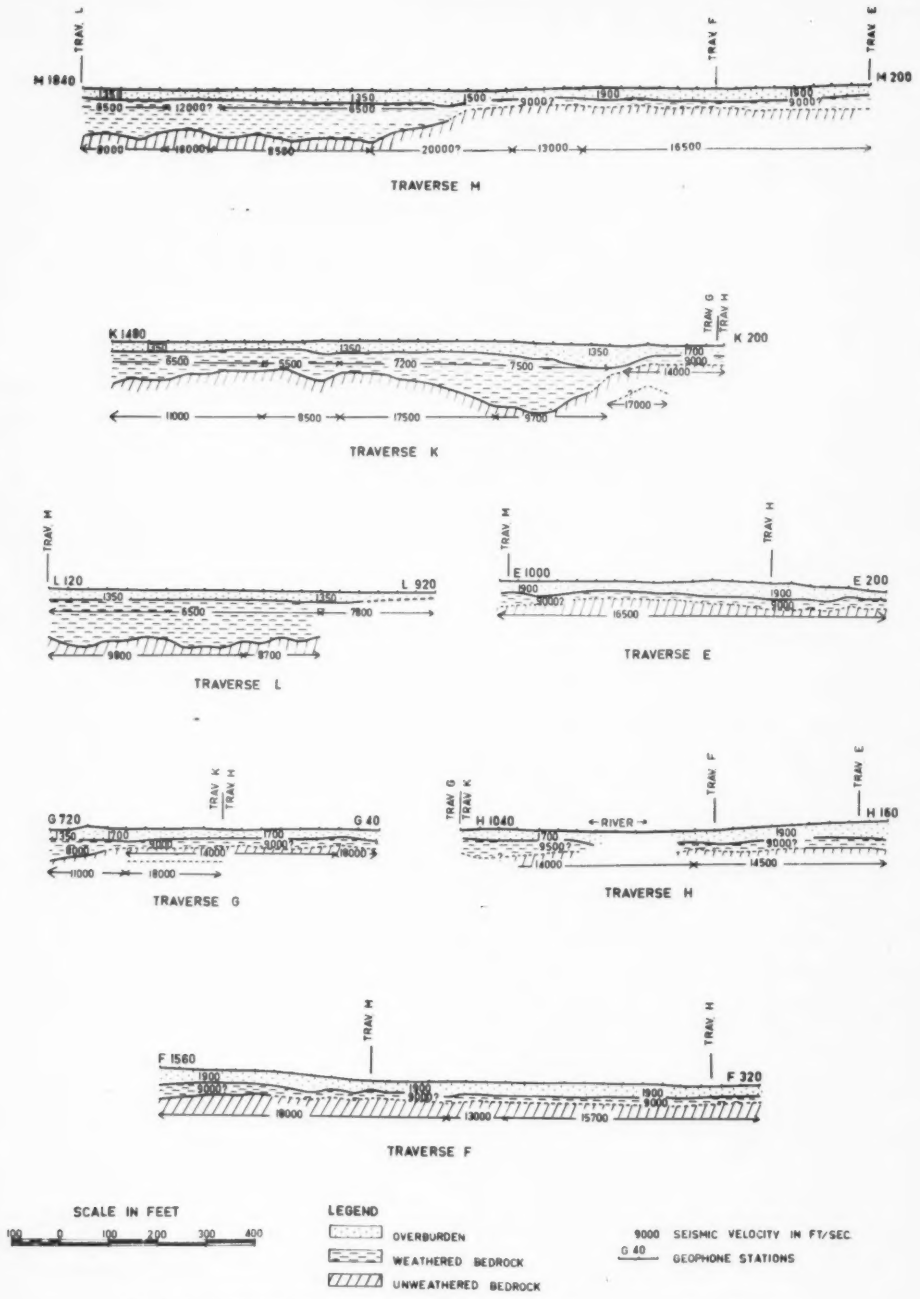

FIG. 5. Cross-sections along traverses showing seismic determinations of weathered and unweathered bedrock and measured seismic velocities.

bedrock" may be from lenses of limestone which could be relatively thin. However, it is reasonable to assume that underlying interbedded sediments, although they may have a somewhat lower velocity, would also be relatively unweathered and have considerable strength. Two cases of higher velocity layers within the "unweathered bedrock" were recorded on traverses *K* and *G*.

Two possible fault zones are marked on Figure 4. The first strikes almost north-south across the middle of the proposed site and is indicated in the seismic results by a substantial increase in the thickness of and decrease in the seismic velocities in the "weathered bedrock" layer to the west of the line shown on Figure 4. This line marks the eastern limit of the supposed fault zone, but the width of the zone is indefinite because the whole area to the west is deeply weathered and crossed by the second supposed fault. The second fault is indicated by low seismic velocities on traverses *K*, *L*, and *M*. This supposed fault has a north-northwesterly trend and is correlated by geologists with the Acton Fault.

A point of interest in the seismic results is the plotting of a thin continuous "weathered bedrock" layer extending over the eastern half of the site. Here, the velocity in the "unweathered bedrock" is between 13,000 and 20,000 ft/sec. The thin overlying layer was recorded only at some weathering spreads and at shotpoints near normal spreads at the southern ends of traverses *F* and *G* where the layer is thicker. The layer was also indicated by later arrivals on some normal and weathering spread records from traverse *F*. This occurred where the first arrivals (of 15,700 ft/sec velocity) were of high frequency but of relatively small amplitude, possibly due to refraction along thin limestone lenses. Where recorded, the layer is generally of the order of 10 to 20 ft thick and may represent partly weathered interbedded sediments overlying the higher velocity beds or lenses. The evidence suggests that the layer may be continuous across this area but that it is masked by the higher velocity "unweathered bedrock."

In the interpretation, the layer was assumed to be continuous, and the depth profiles of both the "weathered" and "unweathered" bedrock were plotted. The time-depths to the top of the "weathered bedrock" were obtained by subtracting the approximate time-thickness of this layer from the calculated time-depths of the "unweathered bedrock." Since the composite depth conversion factor in the calculation of the depth to the "weathered bedrock" is small, the calculated depth is relatively insensitive to the value adopted for the time-thickness of the "weathered" layer. Hence, in this interpretation, the upper surface of the bedrock is estimated fairly closely even in places where the assumed weathered layer may be absent.

Conclusions from the Seismic Results.—It is apparent that the area to the west of the first possible fault is unfavorable for weir foundations. Although the thickness of the overburden here is only slightly greater than to the east, the bedrock appears deeply and extensively weathered and is crossed by two possible faults, one of which is correlated with a major fault between the Ordovician and Silurian strata.

In the area to the east of the first fault much more favorable conditions are present, and the most promising site is in the northern part of the area approximately along traverse *H*. In this area the overburden ranges from 12 to 27 ft and averages 25 ft in thickness. The underlying bedrock appears to consist of a thin "weathered" layer of about 9,000 ft/sec velocity (which probably does not exceed 20 ft in thickness and may be absent), underlain by the "unweathered bedrock" in which the velocity is between 13,000 and 20,000 ft/sec. The velocities in the "unweathered bedrock" are indicative of strong foundation rock even though they may result from lenses of higher velocity rock overlying associated sediments. The "weathered bedrock" layer, if present, may also prove suitable foundation rock.

Subsequent Drilling.—Diamond drilling of the site was carried out in 1958, and the locations of the two drillholes on the site of the survey are shown on Figure 4. The drillholes were located a little away from the geophysical stations, approximately along traverse *H* and near the centerline of the proposed weir. Both holes entered hard calcareous, little weathered mudstone, siltstone, and sandstone immediately below the sandy alluvium. The depths at which this bedrock were intersected were about 17 and 23 ft and are similar to the seismic estimates to the top of the "weathered bedrock" at the closest geophone stations. No appreciable change in weathering was apparent from the drilling, showing that the assumed "weathered bedrock" layer is absent in this particular area.

Example of the Analysis of the Velocity in the Refractor

The part of the centerline traverse of the new Commonwealth Avenue bridge site shown in Figure 6 runs approximately north from the top right hand corner of Figure 4 across the alluvial covered Molonglo valley up to the south bank of the Molonglo River.

In the presentation of the seismic results the surface layers have again been grouped into one layer (the overburden) which has a calculated average velocity between 1,900 and 2,600 ft/sec. The measured velocities in the bedrock refractor range from 6,500 to 18,000 ft/sec. Figure 6 shows the continuous time-distance curves of both the recorded and the corrected travel times, the measured bedrock velocities, the depth profile of the bedrock refractor, and the average velocities through the overburden.

Eight holes were drilled on the proposed bridge site subsequent to the seismic survey. Five of the drillholes are shown in Figure 6. The sixth was drilled just north of the river into bedrock in which the seismic velocity is 8,000 ft/sec. The

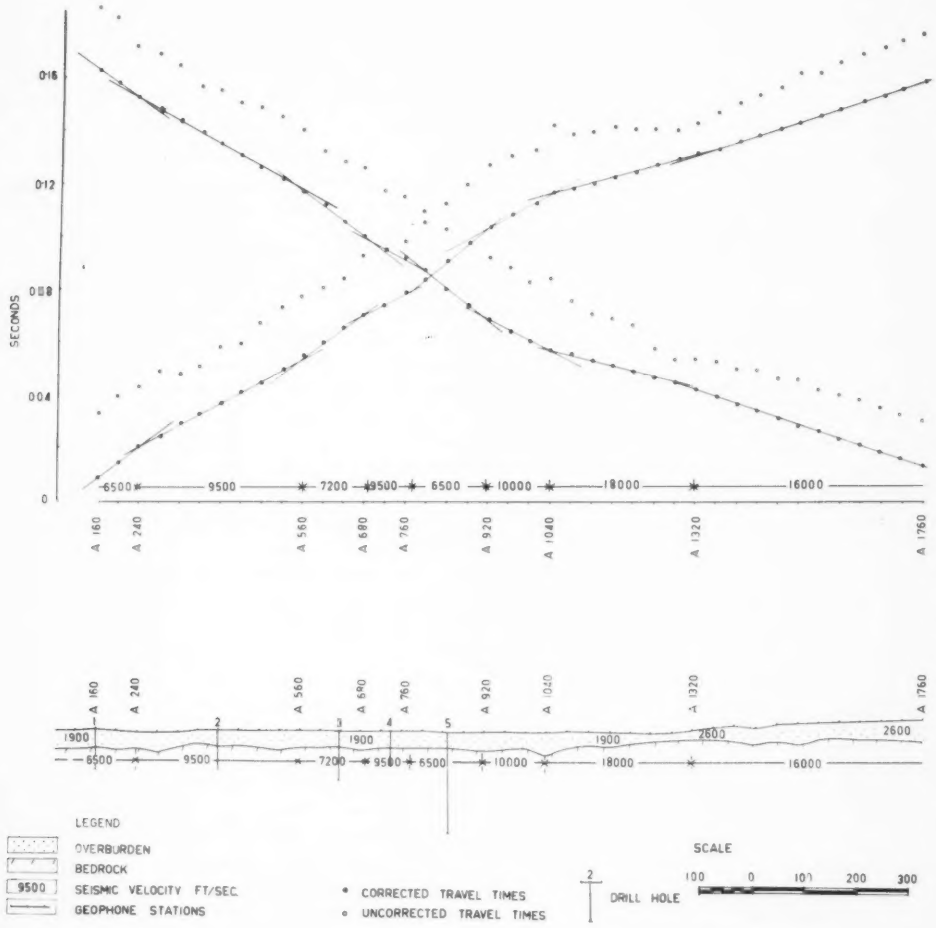

FIG. 6. Cross-section along seismic traverse from survey of Commonwealth Avenue bridge site showing bedrock profile and drill locations together with time-distance curves of recorded and corrected travel times and measured velocities.

two remaining holes were located in the river bed away from the seismic traverses. The results of the drilling are recorded in an unpublished Record of the Bureau of Mineral Resources (Gardner, 1957).

The holes were drilled to check areas of bedrock in which the seismic velocity was in the lower range of 6,500 to 9,500 ft/sec. The bedrock in these areas was shown to be Silurian mudstones and siltstones in which the fracturing and degree of weathering show a direct correlation with the measured seismic velocities. A comparison between the seismic velocities and the type and condition of the bedrock for the six relevant drillholes is shown in Table 1. It is interesting to note that hole No. 4 was drilled into bedrock in which the recorded velocity of 9,500 ft/sec extends approximately 80 ft over only two geophone stations. Holes Nos. 3 and 5 were drilled one hundred feet on each side of hole No. 4 into the lower velocity, more decomposed rock and show that variations of the seismic velocity are delineated fairly precisely within the limits of the geophone spacing used.

The bedrock in which the seismic velocity is 16,000 to 18,000 ft/sec was not checked by drilling on this site. However, the area in which it occurs is just to the northeast of the Acton weir site. It appears probable that the highly calcareous sediments with limestone beds and lenses persist here.

ACKNOWLEDGMENTS

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DEPARTMENTS

DISCUSSIONS AND COMMUNICATIONS

THE SPECIFICATION AND TESTING OF A SEISMIC-REFRACTION SYSTEM FOR CRUSTAL STUDIES*

R. E. WARRICK,† D. B. HOOVER,† W. H. JACKSON,† L. C. PAKISER,† AND J. C. ROLLER†

A new seismic-refraction system built for the U. S. Geological Survey for crustal studies has been tested in the laboratory and shown to meet strict performance specifications for broad frequency response, low noise, high gain, and high dynamic range. The inherent advantages of magnetic recording, with selective filtering on playback, were demonstrated in field tests by the recovery of weak events that otherwise would be obscured by high seismic noise.

SPECIFICATIONS

R. E. WARRICK AND D. B. HOOVER

At the beginning of the U. S. Geological Survey's new crustal-studies program, the need for specialized long-offset refraction instrumentation was recognized. In early summer of 1960, L. C. Pakiser and D. B. Hoover visited numerous geophysical instrument companies and geophysical research groups to determine the state of the art in seismic instrument design. The geophysics departments of California Institute of Technology, Colorado School of Mines, Department of Terrestrial Magnetism of Carnegie Institution of Washington, Lamont Geological Observatory of Columbia University, Stanford University, Stanford Research Institute, and University of Wisconsin provided information on their equipment and offered suggestions for new instruments. With this background, several geophysical instrument companies were visited to find the current practical limitations of seismic instrument design. The special requirements of long-offset seismic recording were discussed with consultants and members of the Geological Survey. Using the data thus obtained, specifications were drawn for seismic instruments especially well suited to the crustal-studies program.

This development was supported by the Advanced Research Projects Agency, Department of Defense, under project VELA UNIFORM.

The complete recording unit includes seismometers, cables, amplifiers, timing equipment, radio communications, and data-storage facilities. The amplifiers, data-display, and storage features are discussed here. The basic seismic recording system consists of eight amplifier channels, a photographic recording oscillograph, and a 14-channel frequency-modulated magnetic-tape recorder. Timing is provided by an electronic chronometer. The shot instant is received from signals transmitted by radio from the shotpoint.

The amplifiers are completely transistorized to achieve freedom from microphonic noises, to reduce power consumption, and to improve reliability. The input circuit of the amplifiers has hum-balance controls to permit reduction is unwanted signals induced by power lines into the long geophone cables used in refraction studies. The system input impedance is about 400 ohms, principally resistive, at 2 cps. Calibrated signal attenuators are provided to allow reduction of overall gain by 84 db in 6-db steps. The overall frequency response is uniform within 3 db between 1 and 200 cps for the oscillograph system and between 1 and 300 cps for the magnetic-tape sys-

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† U. S. Geological Survey Denver, Colorado.

Table 1. Comparison of selected parameters measured with specifications

Parameter	As specified	As delivered
Frequency response (filters out)	3 db down at 1 and 100 cps oscillograph	3 db down at 1 and 200 cps oscillograph 3 db down at 1 and 300 cps magnetic tape
Phase matching	Within 5 millisecond below 5 cps Within 1 millisecond above 5 cps	Equals or exceeds specifications
Noise (internal)	Less than 0.05 microvolts rms in 1 to 20-cps band with 400-ohm input termination	0.04 microvolts in 1 to 26 cps band with 400-ohm input termination
Gain (voltage)	Such that internal noise in 7–9 cps band pass will produce galvanometer spot deflections of 1/16 inch	As specified: 1 microvolt rms input will produce galvanometer spot deflections in excess of 1 inch.
Dynamic range	To permit 8-inch deflection of galvo. spot without distortion	A deflection equivalent to 30 inches would occur before distortion is apparent.
Crossfeed	Greater than 80 db down (oscillograph)	Greater than 100 db down (oscillograph)
Oscillograph timing accuracy	1 part in 10,000	1 part in 10,000

tem. Both high- and low-cut filters are provided for optional use. The high-cut filters have 3-db down frequencies at 9, 13, 18, 26, 37, and 100 cps, with a choice of 18 or 36 db per octave attenuation rate. The low-cut filters have 3-db down points at 3.5, 7, and 14 cps and an attenuation rate of 18 db per octave. The filters are used mainly in playback of wide-band recordings stored on magnetic tape.

No automatic gain control is used. Amplitude measurements can be made directly from the records. The output of each amplifier is divided so that data can be recorded simultaneously on the photographic oscillograph and on magnetic tape. The dynamic range of the amplifiers is 60 db. To handle this large range, dual-level recordings are used. The two levels are separated by 15 db on the oscillograph and by 30 db on the

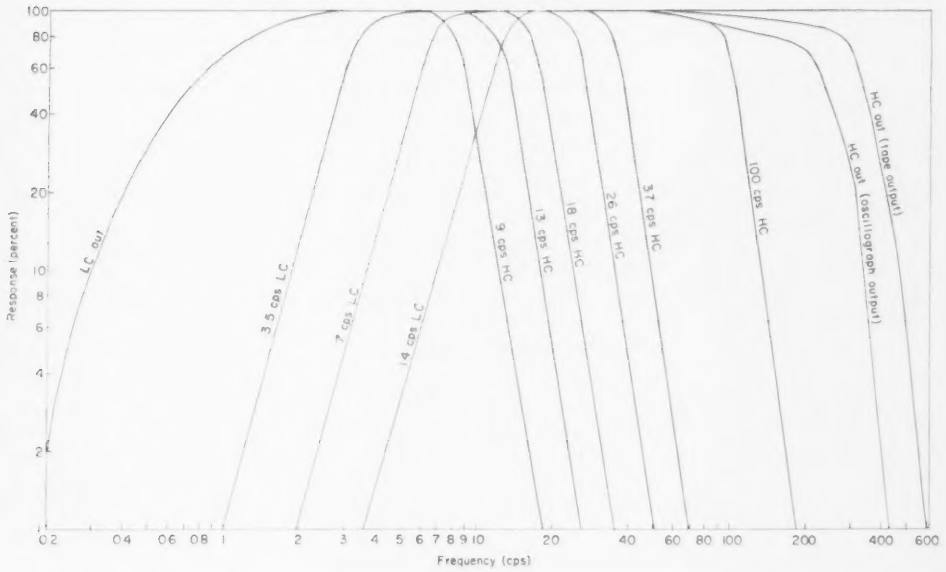

FIG. 1. Composite, normalized frequency-response curves for the new seismic-refraction system. LC, low-cut; filter; HC, high-cut filter.

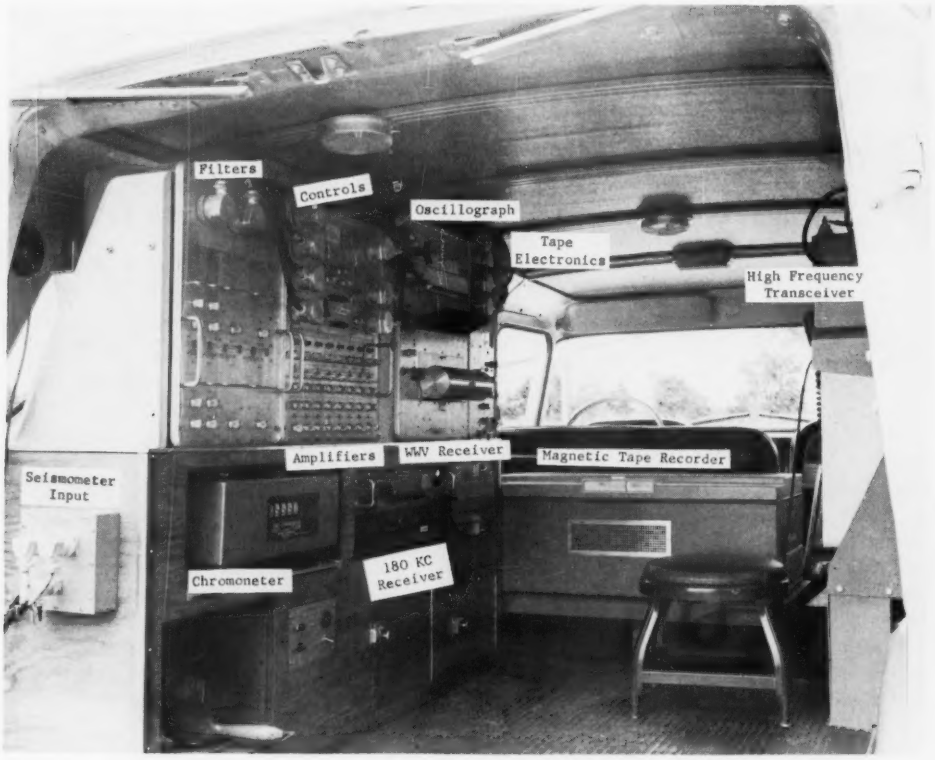

FIG. 2. View of recording truck interior showing seismic instruments.

tape recorder. The choice of the level separation is based on the usable dynamic ranges of the respective recording media. Fourteen channels on the magnetic-tape recorder permit six seismic information channels to be recorded on dual levels. The remaining two channels on the tape are used for a speed-synchronization signal, for timing, and recording the shot instant. The two remaining amplifier channels are recorded on the oscillograph but not on the magnetic tape. These channels are used to record horizontal motion or cross-spread information.

A calibrated oscillator and step-function generator provide means for determining the amplitudes of recorded events and for checking on the proper operation of the system.

A stable electronic chronometer provides a reference to Universal Time. This chronometer is periodically compared to time signals from WWV to determine its drift. Use of the chronometer permits operation when radio communications and WWV signals are not reliable. The shot instant is recorded and referenced to Universal Time at the shotpoint. The recording system is usable over the temperature range of 0° to 120°F with 10 per cent or less change in characteristics over this temperature range.

The recording equipment is of modular design, cased as portable units, and installed in a light truck. The truck contains batteries and the charging system for operation distant from civilization.

The contract for the recording system was awarded in competitive bidding to S.I.E. Division of Dresser Electronics, Houston, Texas. Upon completion of the first unit, acceptance tests were conducted in the contractor's plant from February 17 to 20, 1961, to check system performance. Some of the parameters tested are compared to the specifications in Table 1. A composite frequency-response curve is shown in Figure 1. The interior of the recording truck is shown in Figure 2.

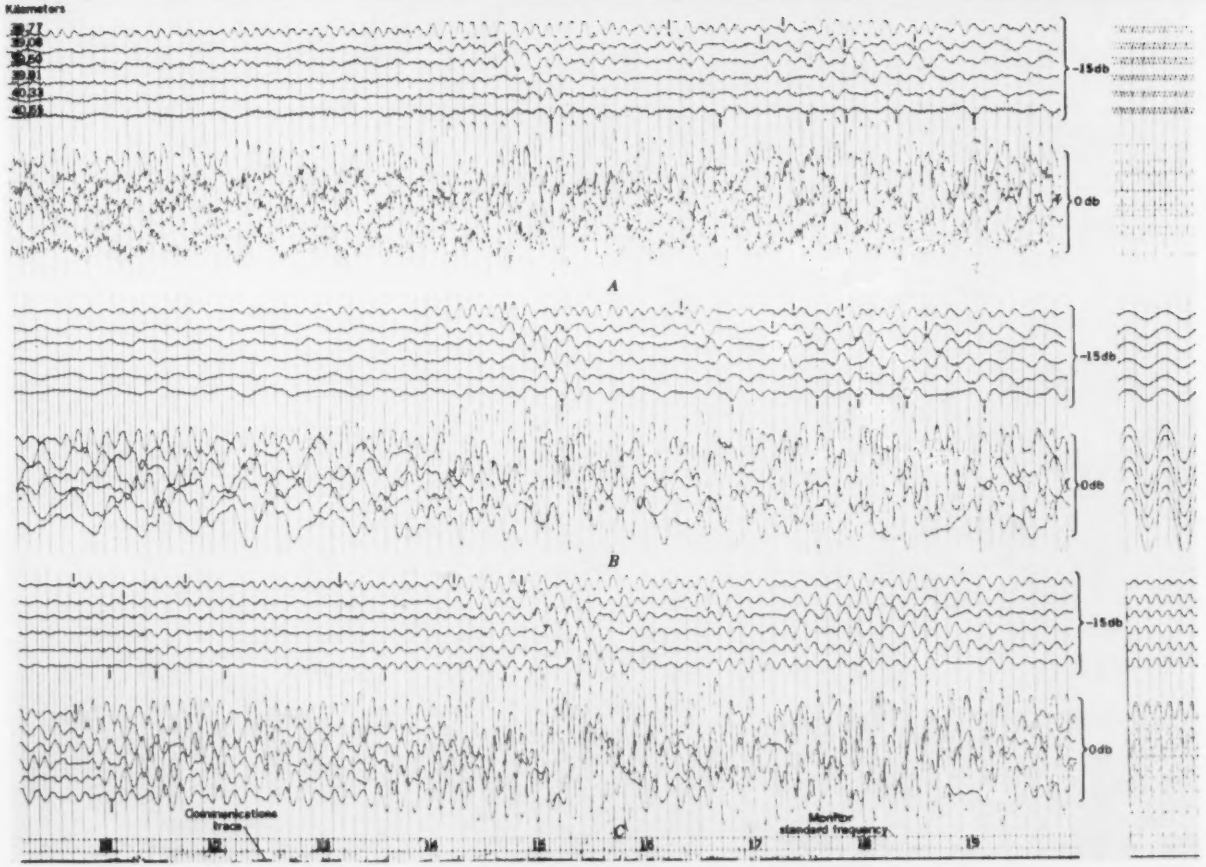

FIG. 3. Magnetic-tape playback seismograms for a 100-lb shot extending from 160 to 200 ft deep, recorded at radial distances of 38.77 to 40.65 km from the shot in an area west of Houston, Texas.

A. High-cut filter, 37 cps; low-cut filter, out.
B. High-cut filter, 9 cps; low-cut filter, out.
C. High-cut filter, 9 cps; low-cut filter, 7 cps.

Attenuation slopes for high-cut filters, 36 db per octave; for low-cut filters, 18 db per octave.

Calibration signals at right are 10 microvolts rms of frequencies 30, 3, and 10 cps for records A, B, and C respectively.

The system met or exceeded all specifications, and delivery was accepted by the U. S. Geological Survey on February 25, 1961, after field tests.

FIELD TESTS

W. H. JACKSON, L. C. PAKISER, AND J. C. ROLLER

Following thorough laboratory tests, field tests in the vicinity of Sealy, Texas, about 50 miles west of Houston, were made to determine the compatibility of the components of the seismic system and associated equipment. The field tests were made using a single shot-point on the property of Mr. Dee E. Brune, Sealy, Texas. We acknowledge with gratitude Mr. Brune's kind cooperation and assistance during the course of the work. Seismometers used for the tests were of the moving-coil type, with a natural frequency of 2 cps, and a sensitivity of about 1.5 volts per inch per second.

The versatility of the new system was demonstrated by the results of a 100-pound shot recorded at a site approximately 40 km northeast of the shotpoint. The charge of $2\frac{1}{2}$-inch, 60 percent, high-velocity gelatin extended from 160 to 200 ft deep in a drill hole. The section penetrated by the drill hole was composed predominantly of clay. At the recording site, a level area about $6\frac{1}{2}$ miles south of Waller, Texas, observations were made with 6 seismometers spaced at 500-m intervals. Seismometers 2 through 5 were along an east-trending road, and seismometers 1 and 6 were offset 75 and 365 m respectively on north-trending crossroads. The shotpoint was at 29°46.0′N., 96°15.7′W.; and the center of the recording spread was at 29°57.8′N., 99°55.0′W.

Because of the high seismic noise, caused in part by strong winds, the system gain was sharply attenuated and a 37-cps high-cut filter (36 db per octave slope) was used in making the recording. The noise level (Figure 3A) was as high as 40 microvolts peak-to-peak when compared with the 30-cps, 10-microvolt rms, calibration signal (28 microvolts peak-to-peak). The dominant noise frequencies on this seismogram were approximately 2 cps and 25 cps.

The first prominent event on the seismogram (Figure 3A) appeared at approximately 15 sec after the shot instant. The apparent velocity of the wave was about 3.8 km/sec, and the frequency was about 7 cps. Later events arriving from 16 to 19 sec had apparent velocities from 2.4 to 3.8 km/sec and dominant frequencies of less than 6 cps. Rice Institute geophysicists (I. H. Cram, Jr., GEOPHYSICS, October, 1961) observed velocities of 2.3 and 3.94 in a sedimentary section 7.3 km thick in the same general area.

Definition of later events was improved by decreasing the high-cut filter from 37 cps to 9 cps (36 db per octave slope) to reject high-frequency noise and by increasing the instrument gain on playback (Figure 3B). Identification of events earlier than 15 sec was especially difficult on this playback seismogram because of the strong low-frequency background noise.

By narrowing the bandpass to between 7 cps (18 db per octave low-cut) and 9 cps (36 db per octave high-cut) the higher-frequency first-arrival energy appeared at about 10.7 sec with an apparent velocity of about 5.6 km/sec and frequency of about 7 cps; but the definition of some of the later, lower-frequency arrivals was reduced. Time and apparent velocity of the first arrivals agreed with those observed by Rice Institute seismologists (op. cit.) and identified as refracted arrivals from limestones of Late Cretaceous age at a depth of about 7 km. The amplitude of the first arrivals was low compared with the background noise before selective filtering. Using the 10-microvolt rms (28-microvolt peak-to-peak) calibration signal as a measure, the amplitude was no greater than 5 or 6 microvolts peak-to-peak. Identification of this event on a conventional broad-band oscillographic record would be difficult, if not impossible.

LETTERS TO THE EDITOR

August 28, 1961

Dr. Nelson C. Steenland
Geophysical Associates International
Box 22007
Houston 27, Texas

Dear Dr. Steenland:

Prior to the Institute at Syracuse last summer for trade association executives, some two hundred associations were invited to send examples of various publications, mailings, brochures, and other items from their offices. The material submitted was divided into five major categories and was placed on exhibit at the Institute.

As chairman of the Exhibit Committee, I am happy to tell you that the Society of Exploration Geophysicists won first place in the category for publications. Inasmuch as the balloting was by trade association students actually enrolled at the Intitute, this is indeed a fine tribute to the excellence of the SEG Yearbook.

We also appreciate the cooperation of SEG in making this material available to our committee so that everyone at the Institute could see it.

Sincerely yours,
EVERETT ALLEN
Executive Secretary
Pennsylvania Hotels Association

"The Editor is most pleased to add that the Business Office's personnel; Messrs. Campbell, Latting, and Hyden; is responsible for the appearance of the Yearbook. So to them are extended sincere congratulations and appreciation."

August 31, 1961

Mr. Richard F. Hagemann
Campagnie Generale de Geophysique
50, Rue Fabert
Paris VII^{e}, France

" . . . Refraction Seismic Prospecting. . . . " by Layat et al August 1961 GEOPHYSICS

Your attention is drawn to some critical comments made by Mr. Francis Campbell of Amerada Petroleum Corporation in a letter to me dated 22 August. Would you please ask the authors to reply to me in such a way that I can publish their explanations along with Mr. Campbell's inquiries? These are quoted below.

"There are two very long, involved sentences; on page 438, second column, beginning, 'Regarding the number of geophones . . . , ' and on page 441, second column, 'We shall merely point out. . . . ' The meaning of these sentences is not clear to me. The style indicates transcription of an oral presentation rather than that of a manuscript prepared for publication.

"In the discussion of anisotropy starting on page 442, the meaning may be clear to readers familiar with the two references, but from what is given I don't see how anisotropy makes a 50% error in offset distance.

"No titles are given for figures. In the discussion of Figure 9 on page 446 just below the figure itself there is the phase, 'the first 300 m/sec of the signal.' The context suggests a time unit of measurement, not a velocity unit.

"Minor points concern—the failure to identify the symbol n or the abbreviation W.Z.; the use of words in technical and non-technical senses without clarification, i.e.—'critical,' and the error in the L. W. Gardner reference which appeared in 1939, not 1959."

NELSON C. STEENLAND
Editor of GEOPHYSICS

Paris, September 14, 1961

Nelson C. Steenland
Editor of Geophysics
Geophysical Associates International
Post Office Box 22007
Houston, Texas

Dear Dr. Steenland:

I have discussed your letter of August 31, drawing our attention to the comments of Mr. F. F. Campbell on the paper by Layat et al, with Mr. Layat, and he has asked me to make the reply.

Basically the faults in this paper can be attributed to undue haste in its publication. I do not believe that we are entirely at fault as we did not press the society for immediate publication. We were under considerable handicap to edit this paper and proofread the galley, as one of the authors was in Rome and the three others were in Algiers. Irrespective of this, it is our fault for not requesting a delay in printing the manuscript.

In reply to the question concerning the sentences on p. 438, this very involved sentence refers to the number of geophones employed and to their spacing within a pattern. Experiments carried out in the Sahara under controlled conditions and in a variety of surface conditions have shown that the number of geophones "n" employed in a pattern is related to:

signal to noise ratio $\alpha\sqrt{n}$.

Once this relation was determined, further experiments with geophones spacing indicated an improvement in signal-to-noise ratio for "n" geophones as the detector interval within a group was increased up to 10 meters. Beyond 10 meters, no significant improvment could be noted. The limiting factor on the improvement and signal-to-noise ratio is the elevation or topographic relief within the detector pattern taken as a whole; and, if the topographic relief is excessive, the geophone spacing must be reduced.

The questionable sentence on p. 441 concerns interpretational procedure. It was necessary to establish certain standards for refraction interpretation so that the results, for any one of the large number of crews operating in the Sahara, could be compared readily with any of the others. It was recognized that most refraction interpretations and procedures were subject to certain intuitive influences and, to a large measure, dependent upon the individual doing the interpretation of the records. A standard procedure was established which minimized the plotting and preparation of graphs and, on the contrary, emphasized mathematical calculations. A system of checks and balances was established so that the interpretated data could be considered reliable, and any questionable data could easily be determined. The computing procedure is such that any errors uncovered do not affect other portions of the survey data and result in only minor modifications in the total result. It is possible, therefore, to make comparisons and to integrate data from distinct and separate areas and exploration programs with confidence.

In the description of anisotropy, the authors relied upon Figure 6 to indicate the effect that could be realized. In Figure 6, the two curves for offset distance (dotted for the calculation not considering anisotropy and solid considering anisotropy) give distances of 3,000 meters and 4,500 meters for the two conditions. The 1,500 meters additional offset that is needed to follow the basement marker with anisotropic media is considered to be a 50% error. Otherwise stated offset distances calculated for the basement marker disregarding anisotropy would be approximately 3,000 meters in the Hassi Messaoud area. Using this offset distance, the basement marker could not be recorded. The anisotropy effect requires that the offset distance for this basement marker must be 4,500 meters which is 50% more than the previous mentioned calculation.

The absence of titles for the figures is a gross oversight and can only be explained by the lack of time available before the paper was published. In addition to lacking titles, we point out the Figures 7a, 7b, 7c, 8a, and 8b have all been printed with the top of the section at the bottom. These five figures must all be inverted. Below is the list of titles for the Figures 1 through 9.

Fig. 1 —Typical surface shot charge pattern.
Fig. 2 —Geophone interval response curve.
Fig. 3 —Refraction layout or spreads and recording sequence.
Fig. 4 —Theoretical limitation upon refraction in the case of non-conformable horizons.
Fig. 5a and 5b—Fault evidence on recordings having varied offset distances.
Fig. 6 —Delay time—Offset distance curve for isotropic and anisotropic media.
Fig. 7a—Refraction record section—Normal galvanometer presentation.
Fig. 7b—Refraction record section—Variable area presentation.
Fig. 7c—Refraction record section—Variable density presentation.
Fig. 8a—Refraction record section showing fault.
Fig. 8b—Same section as 8a shot in reverse direction.
Fig. 9 —Composited refraction traces showing marker character.

On p. 446, the phrase "the first 300 m/sec of the signal" should read "the first 300 millisec. of the signal."

We regret that the symbol "n" was not identified in its context with the number of geophones, it was identified when it refers to the number of shots. Abbreviation W.Z. naturally refers to the weathering zone, in European circles, this is an accepted abbreviation. The ambiguous utilization of the word "critical" is regretted, but stems from a similar ambiguous utilization in French.

Within the reference cited, the names of Mr. Bouchon and Mr. Pommier were misspelled, in addition to the error in the date of Mr. Gardner's article.

The authors sincerely regret the multitude of faults in the printed article. They hope that the above explanations will suffice and will clarify any misunderstandings.

Sincerely yours,
R. F. HAGEMANN

REVIEWS

REVIEWS COMMITTEE

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Isostasy and Isostatic Hypotheses, E. N. Lyustikh, (Translated from the Russian original published by the Geophysics Institute of the Academy of Sciences of the USSR), American Geophysical Union, New York, 1960, 119 pp., $6.50.

This book of 119 pages and several graphs and maps consists of ten chapters in which the theory and practice of the isostatic theories and their significance to the geophysical studies of the earth's crust, and the substratum close to it, are handled.

In the first two chapters, the principles of isostasy and the methods used are briefly explained in an elementary way, customary in the textbooks on isostasy. Several pictures indicate the difference between the Pratt and Airy hypotheses; Airy's assumption has been presented both in case the earth's crust has only one layer, as well as in case it has two layers of different density.

In Chapter III, the author deals with the influence of the geological processes on isostasy. He divides the geological processes which affect the gravity into three groups: horizontal displacements of mass in large volumes—as erosion and sedimentation; change in volume of material at depths; change in density without change in volume—as the horizontal movements of mass.

In Chapter IV, the author gives a historical review of the isostatic theories of Pratt, Airy, Hayford, Bowie, and Vening Meinesz and deals in detail with the theory of Lukashevich. He criticizes strongly the "dough" theories of Pratt and Bowie, and accepts in principle the floating theory of Airy with its roots of mountains and antiroots under the oceans. As to the mechanism of the isostatic equilibrium, he is against the "buckling theory" of Vening Meinesz and accepts the theory which "the Russian scientist and revolutionary" Lukashevich presented in 1908. The basic difference between these theories is obviously this: According to Vening Meinesz, the crust folds downward in the substratum in the beginning of the mountain-building cycle producing the root formations which then will gradually be uplifted, (because the isostatic equilibrium is disturbed) and create the mountains, while Lukashevich says, "when the orogenic phase begins, the geosyncline is crushed between neighboring encroaching segments of rigid crust. The material in the geosyncline is compressed into folds and is squeezed not only upward into mountains but also downward, forcing the subcrustal material out of the way and forming a thickening of the crust necessary

to support the mountain range in an isostatic state. As the mountain range is destroyed, isostatic forces raise it, exposing new, deeper parts to the forces of erosion. With this 'buoying up' of the mountain range, the lower projection of the crust (the 'root' as it came to be called later) naturally grows smaller." In other words, according to Vening Meinesz the roots of the mountains come first, the mountains themselves later; while according to Lukashevich the roots and mountains are brought about simultaneously.

Chapter V, "The Isostatic Status of the Earth," is based mostly on the geoid studies of Tanni of 1948 and of Zhongolovich of 1952—both very valuable papers. The distribution of the mean free-air and Bouguer anomalies and of mean elevations and depths of the topography are shown with maps, tables, and graphs.

As is natural, Lyustikh came in his analysis in broad lines to similar conclusions as Helmert, Hayford, Bowie, Vening Meinesz, Jeffreys, myself, and other western geodesists. We agree with him that the average free-air anomalies of not too small blocks cannot differ very much from the average isostatic anomalies more than 40 mgal but usually much less. His statement that, in case the isostatic equilibrium does not prevail the free-air anomalies should approach $0.11\ h$ mgal, (which has been shown, for instance, by the detailed study of Uotila, 1959)—h elevation of stations in meters on land, and -0.07 mgal at sea—is correct. In case of complete equilibrium the Bouguer anomalies are almost the same but with opposite signs.

In several of my publications, I have emphasized that the high mountains and the ocean basins are compensated to approximately 85-90 percent. Lyustikh goes still further in mentioning that because the average free-air anomalies on land are +9 mgal and the average Bouguer anomalies −87 mgal, and at the oceans average free-air anomalies −3 mgal and Bouguer anomalies +230 mgal, the continents are compensated 91 percent and the oceans 99 percent [p. 71].

As is known, Helmert, Krassowsky, myself, and several other authors have shown that the earth might be triaxial. The Russian scientist, Zhonglolovich went further in developing the free-air anomalies in spherical harmonics to eighth order in 1952. The western scientists were, in general, of the opinion that the gravity material existing a decade ago, particularly because of the huge gaps in the oceans of the southern hemisphere, was too scarce to permit a reliable development of the gravity anomalies in high order spherical harmonics. I am still of that opinion.

In Chapter VI, "The Causes of Zonal Harmonics," Lyustikh shows that the mean free-air anomalies, in case we apply the spherical harmonics, are smaller than in the case when the usual spheroidal gravity formula is used. This is, of course, correct, as it should be, because the spherical harmonics to the eighth order partly explain the long-period gravity anomalies. Helmert in 1915, myself in 1924, Tanni in 1948, and other geodesists have shown that the mean gravity anomalies become essentially smaller when we use the triaxial gravity formula.

We also agree with Lyustikh that "the cause of zonal free-air anomalies cannot lie in the crust, it must be sought in deeper shells of the earth," an opinion which can be found in a great many western publications.

In Chapter VII, "Compensation and Overcompensation," the author presents statistics on the basis of Hayford's system, depth of compensation 113.7 1, of Heiskanen's system, the thickness of the earth's crust, T=40 km, and of Vening Meinesz's regional system, about the percentage of the over- and undercompensation in oceans, 325 computation points, and in East Africa, 13 computation points. The results indicate that the isostatic equilibrium is, practically speaking, complete. Exceptions can be found almost only in the tectonically disturbed areas, as for instance in the East Indies and the West Indies, which certainly are rather far from equilibrium.

In Chapter VIII, the author makes an analysis about the error sources of the isostatic anomalies. The problem is handled in the customary way. It might be mentioned that the author belittles the western scientists. "An overwhelming majority of foreign authors [who] adopt without proper verification the postulate that isostasy is of decisive importance in geotectonics. . . ." in contrast to the "Soviet investigators who are far from employing such defective methods." [p. 94] He continues, " . . . on the other hand [however], it should be noted that we in the Soviet Union have paid too little attention to the problems of isostasy, and we have not yet fully considered its importance."

Vening Meinesz, myself, and several other geophysicists have emphasized repeatedly that the normal thickness T of the earth's crust is not the same everywhere. The computations show, in fact, that T varies in the continents from 20 km under the Alps to 50 km in some parts of the United States. Lyustikh is against this opinion regardless of the gravimetric and seismic facts and sound reasoning. Because different areas of the earth are formed by different phenomena and processes, it is only natural that the thickness of the earth's crust cannot be the same everywhere. Because of these fac s, we have emphasized several times that different regions of the world have to be studied separately, as Lyustikh recommends. To the geodetic purposes we have for practical reasons, however, used the same normal thickness value (30 km), which seems to be a good average, everywhere.

In Chapter IX, "The 'Emergence' of Fennoscandia," Lyustikh claims that the land uplift in Fennoscandia is not in relationship with the gravity anomalies, so that isostasy has nothing to do with these anomalies. I can hardly accept this opinion, because the land uplift of Fennoscandia and the glaciers in Greenland and Ant-

arctica seem to be in excellent agreement with the isostatic compensation. Because of the trend of Fennoscandia toward the isostatic equilibrium which was disturbed during the glacial period, the land is still uplifted there about one meter per hundred years. On the other hand, the earth's crust in Greenland and Antarctica has sunk during the ice load, as the facts show that the glacier's underboundary is now, in many places, essentially below the sea level. Obviously, the continents of Greenland and Antarctica will also uplift if and when the ice caps melt.

In the last chapter, "The Role of Isostasy in Geotectonics," the author emphasizes the theory of A. D. Arkhangel'ski and claims that the western scientists have overestimated the significance of the isostasy in the development of the earth. He says, "The isostasy plays only a secondary role in the development of the earth though far from being a negligible one." This statement sounds strange when we think that the isostatic compensation explains almost completely—as Mr. Lyustikh emphasizes—the existing mean gravity anomalies of the mountains and ocean basins. Without the isostatic adjustment, the mountain building obviously would have differed essentially from the existing one.

* * *

I personally am pleased to realize that Dr. Lyustikh has referred to my several publications and to my colleagues and students, Erola, Hirvonen, Niskanen, and particularly, Tanni. He has, among other things, reprinted Tanni's maps showing the isostatic mean anomalies of $1°\times1°$ and $5°\times5°$ squares.

It is obvious that such globally important phenomena as the isostatic equilibrium have been studied in many countries; in the west as well as in the east. Therefore, one understands that more or less similar ideas are created by scientists of different countries. Because of the language barrier, it has been impossible for the western scientists to follow in detail what our eastern colleagues have published. Obviously, the eastern scientists have had similar difficulty in finding out the achievements of the western countries. This fact explains, for instance, the following statements of Dr. Lyustikh. He claims that "Zhongolovich [in 1952], was the first to show that the free-air anomalies depend on the elevation" and Zhongolovich "has also shown that gravity anomalies increase with elevations." In fact, this relationship has been shown already at least by I. Bonsdorff in 1916, by William Bowie about fifty years ago, Sir Jeffreys about thirty years ago, and by myself in several of my publications since 1926. Also Lyustikh says (page 41) that "Many investigators (Heiskanen for example) developed isostatic hypotheses of more or less restricting character. . . . Generally these hypotheses followed Lukashevich (without mentioning his name) sometimes with some additions or modification." In fact, I first heard of the works of Lukashevich only some months ago, so it was impossible for me to follow his ideas in 1924 or later.

Naturally, I am in several respects of different opinion than Dr. Lyustikh concerning the details of isostatic principles and methods, but I am very glad that he has written this book and that it has been translated. Certainly I will recommend this book to my colleagues. I hope that more cooperation between the western and eastern geodesists will be possible than up to now. I hope also that the gravity material of the eastern geodesists would be available to the western colleagues to the same extent as the western material is available to the eastern scientists.

W. A. Heiskanen
Ohio State University
Columbus, Ohio

The Time Term Approach to Refraction Seismology, P. L. Willmore and A. M. Bancroft, *The Geophysical Journal of the Royal Astronomical Society*, Vol. 3, No. 4, 1960, pp. 419–432.

This paper describes a refraction method for calculating the depth under a network of shotpoints and receiver points not in straight lines. It also describes a system of making these calculations, which is applicable to present day electronic computer techniques. The problem is to determine the constants in a system of equations in which the time between any shotpoint and any receiver is equal to the "time term" at the shotpoint plus the "time term" at the receiver plus the distance between the shot and receiver divided by the velocity of the refractor. The time term is the familiar quantity in refraction work which consists of the depth to the refractor times the cosine of the angle of incidence divided by the velocity in the upper layer.

The advantages of the method are said to be that the equations can be solved without requiring the shotpoints and stations to be laid out in a particular pattern, that the maximum amount of information is obtained from the data, and that the requirements for making simplifying geological structure assumptions are minimized. The equations are developed for calculating the velocity of the refractor from an array of shotpoints shot into an array of receiving points. The ambiguity of the value may be removed if several points are both shotpoints and receiver points, or if some known geological information relative to the depth of the refractor is available.

The mathematics is developed for a two-layer case, but it is stated that the principle may be extended to allow for increase of velocity with increasing depth. However, surely this would complicate the procedure and require a larger computer to take care of the many calculations.

The method is extended for use in areas of steep dip. However, the example shown in the figure was poorly chosen because the raypath is indicated as entering the

refractor and departing from the refractor in minimum areas rather than in maximum areas, as would be the case of a refracted wave.

The description of the total procedure is enhanced by the use of an example problem which consists of a spherical surface outcropping at one point, with shotpoints and receivers scattered in different directions and at different distances. By using such a mathematical model it is possible to determine the exact times and distances that should be read were this a field example. From these values then the method can be applied and its accuracy checked. The method consists of making the first approximation and then repeating with a second approximation and continuing to the desired accuracy. However, it is interesting to note that on the second approximation the velocity of the refractor was determined within 2 percent and it is quite clear that the solution is converging rapidly.

A method is described whereby the errors in the system can be identified and for the most part evaluated or eliminated. The following working rules are suggested for maximum utilization of this method:

1. Both the shotpoints and the receiving points must form extended patterns to provide adequate determination of the velocity in the marker layer.

2. Locations where maximum accuracy is desired should be bracketed by control points, for the time terms on the fringe of the survey will be less reliable.

3. Do not move receiver points too frequently between shots as maximum accuracy is achieved by observing the greatest possible number of shots into each receiver location.

4. Arrange for some shotpoints to be the location of receiver points when other shots are being fired so as to enable the reduction of ambiguity. If this is impossible, information about the marker layer should be known at a control point.

The authors make an incomplete survey of the literature and seem to feel they have an improvement over all methods. Their method appears to be satisfactory for solving problems where an array of shotpoints and receivers are used in the manner described. However, it appears to have little advantage over other available methods for exploration problems where an in-line or a regular pattern of shot and receiver locations is used.

Albert W. Musgrave
Mobil Oil Company
Dallas, Texas

Seismic Waves in the Region near Explosive Origin, Harumi Aoki, *Journal of Earth Sciences, Nagoya University*, Vol. 8, No. 2, 1960, pp. 120–173.

The author is concerned with the mechanism by which the short, transient pulse of pressure from an explosive detonation is transformed into a train of oscillatory waves in rock. He assumes that this occurs in an inner zone of crushing and an outer zone of fracture. By assuming that the rock behaves plastically in these zones and not outside of them, he is able to develop theoretical wave shapes of the general nature of observed seismic pulses. Their predominant periods increase with the size of the shot and with the radius of the fractured region, and otherwise resemble typical seismic pulses. The duration of the oscillation depends critically on the ratio of Lame's constants, λ/μ. Although his experiments were in clay, analogous results would be expectable in solid rock.

Although the experimental results correlate very well with the theoretical predictions, the amount of data gathered appears to be relatively small. Straight lines are drawn through as few as four scattered points in some cases. Under these circumstances, it is difficult to conclude how perfectly the theory explains the observed seismic phenomena.

B. F. Howell, Jr.
Pennsylvania State University
University Park, Pennsylvania

Mercury Barometers and Manometers, W. G. Brombacher, D. P. Johnson, and J. L. Cross, National Bureau of Standards, Monograph 8, May 20, 1960, 59 pp., $0.40.

This monograph assembles pertinent data on the design, operation, and accuracy of mercury barometers and manometers. It describes the operational features of commercial instruments and emphasizes the aspects that are critical for precision and accuracy.

Nomenclature, definitions, the physical principles of pressure and its measurement, and the properties of mercury are briefly but adequately covered in the opening sections preceding the detailed descriptions of the various types of barometers and manometers. Sources of error are described in considerable detail. These include scale, temperature, gravity, capillarity, vacuum errors, and return gas column. Test methods for detecting errors are presented, as well as the basic formulae and extensive tables needed for correcting the various errors.

Sixty-five literature references are included, which probably represent but a fraction of the information sources consulted in assembling this highly informative monograph. No other single work contains as much practical information of value to users and manufacturers of barometers and manometers. Some of the information presented appears in print for the first time. Every scientist and engineer concerned with manometric or barometric pressure measurements will find this monograph to be a valuable laboratory asset and it undoubtedly will become the standard operational handbook for this specific field.

Two relatively minor shortcomings are evident. Apparently the monograph is intended for those already acquainted with the variety of instruments described, because, although the descriptions explaining the principles of their operation are commendable for their clarity, illustrations of the various commercial species

are not included. Such illustrations would go far towards satisfying the curiosity aroused in the less experienced reader. A more serious omission is the exclusion of the McLeod gage from the array of mercury manometers described. Most of the operational precautions and errors discussed are applicable also to the McLeod gage, and the inclusion of a brief section on this instrument would have substantially increased the value and audience of this monograph.

S. R. Silverman
California Research Corporation
La Habra, California

The Precambrian Geology and Geochronology of Minnesota, Samuel S. Goldich, Alfred O. Nier, Halfdan Baadsgaard, John H. Hoffman, and Harold W. Krueger, University of Minnesota, Minnesota Geological Survey, Bulletin 41, Minnesota Press, Minneapolis, 1961, xxi+193 pp., $4.00.

Ever since the pioneering geologic studies of Lawson and Logan in the 1800's, the Precambrian Shield of Canada and the northern United States has been under attack by scores of scientific teams and individuals bent on unraveling the complexity and reconstructing the sequence of events concerning the oldest rocks of the North American continent.

In this most recent contribution on the subject, Goldich et al., combine the talents of field workers that have gone before with the modern techniques of today's geochemists and field researchers to make a most important contribution to the understanding of the evolution of the continent.

Whereas the scope of the project could not possibly include the entire Shield area, the work does make a good start in that direction. Surely, it will provide stimulus for further work by the Canadians and it will provide a standard of comparison for all Precambrian investigators.

In addition, those particularly interested in stratigraphic and structural Shield geology will welcome the lengthy bibliography that combines references from 1870 to 1960. The volume is extremely timely for it illustrates clearly the need for correlation between field relationships and radioactive age determination, that is, the means of tying relative sequence of events with actual dates. Besides the evaluation and review of potassium-argon and rubidium-strontium age determination methods, calculated ages for areas throughout the state are combined in one volume with a rather complete up-to-date list of age determination references.

Some geologists will be disappointed that the Precambrian has not been subdivided into more eras than the long-standing three-fold division. Nonetheless important unconformities are dated at 0.6 billion years (Paleozoic-Precambrian), 1.7 billion years (Penokean orogeny), and 2.5 billion years (Algoman orogeny) which correspond to major breaks long recognized. Other breaks dated at 1.1 and 2.6 billion years correspond respectively to the Grenville and Laurentian orogenies.

Revision in nomenclature, re-correlation of rock units, and re-emphasis on certain unconformities, combine with actual age assignments to make the volume most interesting to geochemists and geologists alike.

Donald M. Blue
Western Geophysical Company of America
Los Angeles, California

Field Geology, 6th Edition, Frederick H. Lahee, McGraw Hill, New York, 1961, xxxi+926 pp., $10.75.

SEG readers will be greatly disappointed if they had hoped for adequate recognition of their specialized disciplines in Lahee's 6th edition. Of 65 post-1952 entries in the bibliography, only eight relate to geophysical practices or methods and several of the important recent contributions are conspicuous by their absence. The 61-page chapter entitled Geophysical Surveying, again, as in preceding editions, brings up the rear in this volume and contains an out-of-proportion discussion concerning gravity, magnetic and electric methods. Seismic surveying, which accounts for the bulk of the industry's business, is treated by a discussion approximately 10 years out of date, including a four-page account of the now almost archaic fan shooting methods for salt dome location.

In short, the 6th editions's emphasis on geophysics is a reflection of the attitude of geologists towards the geophysical profession ever since physics and instrumentation have invaded the geologists' private world.

Holders of the 5th edition will have little need to purchase the 6th for but 16 new figures have been included in the 841 total and only minor changes and additions were made in the definition of geologic terms. Indeed, much of the "new" discussion includes concepts and ideas that have been in practice for many years and which are included in standard classroom texts. Among such "new" terms are turbidity currents, soil profile, biologic facies, pluton, lopolith, phacolith, ring dike, cone sheet, metamorphic facies, granitization, and wrench fault. Of the 65 new references, many are newer editions of standard texts and general references and a high percentage relate to sedimentary environments and primary structures.

Whereas Lahee's volumes are always important contributions to the beginning field geologist, it is felt by this reviewer that another edition was not necessary at this time unless complete, up-to-date revision was made in certain areas, such as geophysical and subsurface surveying and photogeology, and that other expanding areas of survey and exploration be introduced such as geochemistry, paleomagnetism, and oceanography.

Donald M. Blue
Western Geophysical Company of America
Los Angeles, California

PUBLICATIONS RECEIVED

BOOKS

The Rare Earth, edited by F. H. Spedding and A. H. Daane, John Wiley and Sons, Inc., New York, $14.75.

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MEMORIAL

EWIN D. GABY

An automobile accident on the afternoon of May 30, 1961, in the outskirts of Jackson, Mississippi, claimed the life of Ewin D. Gaby, Sr. The news of his sudden passing came as a great shock to his family and to the many friends he had acquired through the years.

Ewin was born on September 5, 1909, in Mount Washington, Mo. He lived most of his early years in several towns in Texas with the majority of the time being spent in Bryan and Dallas. He attended Bryan High School where he was captain of the debate team and played varsity tennis and basketball. After graduating from high school in 1926, he moved to Dallas and attended Southern Methodist University. He received his B.S. Degree from S.M.U. in 1930. While there, he spent most of his spare time as a laboratory assistant and was a member of Theta Sigma National Science Honorary Fraternity. This early interest in things scientific continued throughout his adult years and was a dominant influence in connection with his life's work. After working a short time as a computer on a GSI seismic party, he returned to school enrolling at the University of Texas for post-graduate studies in his major subject—Chemistry.

Returning to GSI, about a year after he left, he worked for the next several years on seismic parties in many locations in several different states—Oklahoma, Louisiana, Mississippi, Alabama, Texas, and Tennessee. He served in the capacities of computer, driller, surveyor, and party chief. In 1942, he was made Supervisor for GSI of the Louisiana-Mississippi-Alabama, District with headquarters initially in New Orleans and later in Jackson.

In 1947, Ewin and a group of long-time associates formed Delta Exploration Company to conduct contract geophysical operations. Ewin served as President of this organization from the time of its inception until his death. Under his leadership, Delta developed into one of the industry's most respected geophysical companies and expanded its operations from a modest start in Louisiana and Mississippi to locations in all parts of the world.

Ewin's wife, Gertrude, whom he married on Christmas Eve, 1930, was a devoted companion and inspiration to him during their 31 years together. Their marriage was blessed with two children, Ewin D. Gaby, Jr., and Sarah Ann Gaby Mills, both of whom now reside in Jackson, Miss. Ewin was a devoted husband and father. He was inordinately proud of his four young grandchildren who were a continuing source of pleasure to him.

In addition to his wife and two children, Ewin is survived by one brother, Phil P. Gaby, of Tucson, Arizona, who is himself a well-known geophysicist.

Ewin was a builder. He had the desire and ability to improve, to create, to do the job better, which was abetted by his abundant energy and enthusiasm. He was a dedicated exploration geophysicist. He neglected no facet of the business, be it field operations, interpretation, instrumentation, research, organization, or contract-client relationship. During his long career, Ewin made many contributions to geophysics. While he was considered an "old-timer," he always kept a "weather eye" out for new ways of accomplishing geophysical objectives and for applications of new techniques.

Business responsibilities notwithstanding, he still found time for outside activities. He attended Galloway Memorial Methodist Church in Jackson, where he was a member of the official board. He was active in church affairs, especially with regard to the church supported Millsaps College. He was a member of AAPG, SEG, and the Jackson Rotary Club. He was chairman of the International Contact Committee of the latter oragnization.

About 1950, golf became a consuming interest. He

worked with characteristic enthusiasm at improving his game and became a much better than average player.

One of his last personal "projects" was the building of a beautifully equipped personal greenhouse from which he and Gertrude derived a great deal of pleasure in the successful cultivation of gloxinias and several varieties of orchids.

Ewin's pleasant personality, his contagious sense of humor, and his wide range of interests attracted a multitude of friends during his lifetime. He will be deeply missed and always remembered by everyone who was privileged to know him.

J. A. Harris

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,988,690. A. W. Love, R. W. Baldwin, and A. A. Brant. Iss. 5/13/61. App. 8/17/56. Assign. Newmont Mining Corp.

Method and Apparatus for Geophysical Exploration. An electrical prospecting system in which a-c is applied to a pair of current electrodes and the a-c voltage between two intermediate electrodes picked up and compared in phase with the exciting current by means of a two-phase synchro with a potentiometer and differential amplifier.

U. S. No. 2,988,691. E. O. McAlister, R. L. Broxholme, and R. L. Myers. Iss. 6/13/61. App. 2/20/57. Assign. The Anaconda Co.

Geophysical Exploration. An electrical prospecting system in which a regular succession of current pulses of successively opposite polarity are applied to the earth at a pair of transmitter electrodes and the voltage picked up between a pair of distant receiver electrodes, the ratio of the integrated product of voltage and time at the receiver electrodes during arriving charging impulses to the similar integrated product of voltage and time during the interval between charging impulses being measured.

GEOCHEMICAL PROSPECTING

(See patents 2,983,586 and 2,983,587 listed under WELL LOGGING.)

GRAVIMETRIC PROSPECTING

U. S. No. 2,986,036. F. N. Spiess. Iss. 5/30/61. App. 12/7/56. Assign. The Regents of the University of Calif.

Method and Apparatus for Measuring Acceleration in the Ocean. A system for measuring gravity at sea using a gravimeter that controls the frequency of an oscillator whose oscillations are counted, the instrument being lowered from a boat and adjusted to have neutral buoyancy in sea water and provided with a sinker that is automatically dropped when a predetermined water depth is reached, and the instrument read with the cable slack so that motion of the boat does not affect the instrument.

MAGNETIC PROSPECTING

U. S. No. 2,983,865. F. Wenner. Iss. 5/9/61. App. 4/1/46. Assign. U.S.A.

Mine Detector. A magnetic gradiometer having a rotatable frame that carries two spaced high-permeability cores mounted parallel to the axis of rotation of the frame, the cores being wound with series-connected coils connected to an amplifier and indicator, and the frame rotated by a motor.

U. S. No. 2,984,783. S. F. Singer. Iss. 5/16/61. App. 10/27/50. Assign. U.S.A.

Magnetic Orienter and Magnetic Guidance Device for Missiles. A system for determining the orientation of a craft with respect to the earth's magnetic field using a total-field magnetometer and coils fixed on the craft affecting the magnetometer, with current through the coils successively turned on and reversed by a programming switch and the change in magnetometer output telemetered to ground.

U. S. No. 2,990,513. J. C. Arnold. Iss. 6/27/61. App. 9/2/58.

Magnetometer. A magnetometer having two coaxial high-permeability bars with a gap between them through which an electron beam is directed and which impinges on a split target, the magnitude and direction of the magnetic field being determined from the direction and magnitude of the current to the two sides of the target, and the reading initially adjusted to zero by a buck-out winding on the bars.

RADIOACTIVITY PROSPECTING

U. S. No. 2,983,817. J. W. Earley, C. W. Tittle, and A. R. Graham. Iss. 5/9/61. App. 7/23/56. Assign. Gulf Research & Development Co.

Neutron-Capture, Gamma-Ray Prospecting Method. A radioactivity prospecting method in which the degree of mineralization of igneous and metamorphic rocks is

† Gulf Oil Corporation, Patent Department.

determined by exposing equal weight rock samples taken at spaced points of the rock body to identical slow neutron flux and concurrently measuring the intensity and energy of neutron-capture gamma rays.

U. S. No. 2,983,818. J. M. Constable. Iss. 5/9/61. App. 10/22/57. Assign. Electronic Products Co.

Radiation Meter. A G-M tube circuit for high intensity radiation in which the tube is energized with short pulses and the resulting tube current compared with the energizing pulses in a coincidence circuit whose output is indicated.

U. S. No. 2,984,745. S. A. Scherbatskoy. Iss. 5/16/61. App. 12/22/55.

Directional Radiation Detector. A system for measuring the density of soil or well wall by irradiating the ground with a source of fast neutrons and measuring the induced gamma radiation by means of a directional array of detectors having a central phosphor and surrounding phosphors with photomultipliers connected to a coincidence counter.

U. S. No. 2,985,785. S. D. Softky. Iss. 5/23/61. App. 4/18/58. Assign. Tracerlab, Inc.

Low Background Counter. A counter for detecting beta activity of a gas having a cup-shaped envelope made of epoxy resin mixed with petroleum-derived lampblack, a central anode, and a thin cathode coating on the inner surface of the cup.

U. S. No. 2,986,635. W. W. Schlutz. Iss. 5/30/61. App. 3/30/56. Assign. General Electric Co.

Radiation Detector. A scintillation type radioactivity detector in which a unidirectional electric field is applied to the luminophor to enhance the intensity of the light pulses produced.

U. S. No. 2,986,636. R. L. Carlson and C. A. Crafts. Iss. 5/30/61. App. 8/15/57. Assign. Robertshaw-Fulton Controls Co.

Linear and Logarithmic Amplifiers for Compensated Ionization Chambers. A circuit for a compensated ionization gauge in which square wave plus and minus voltages are applied to the outer electrodes which are connected to an a-c amplifier whose output is proportional to the incident neutron flux.

U. S. No. 2,986,638. B. D. Lee. Iss. 5/30/61. App. 1/18/55. Assign. Texaco Inc.

Prospecting Using Gamma Ray Detection. A system for automatically correcting an airborne radiation survey meter for altitude by recording the radiation indication and the altimeter indication on a common record tape and playing the signals back with playback heads longitudinally displaced to correct for lack of simultaneity of the measurements.

U. S. No. 2,986,640. J. F. Grimm. Iss. 5/30/61. App. 2/10/58. Assign. Tung-Sol Electric Inc.

Radiation Meter. A circuit for an ionization chamber having a source of potential connected in series with a constant-current component and a resistor, with the ionization chamber connected across the constant-current component, and an electrostatic voltmeter connected across the resistor.

U. S. No. 2,988,639. H. Welker and R. Gremmelmaier. Iss. 6/13/61. App. 3/9/56 and 3/6/57. Assign. Siemens-Schuckertwerke Aktiengesellschaft.

Method and Device for Sensing Neutrons. A neutron detector having a semiconductor connected to a battery and indicator, one of the elements of the semiconductor being an element that is made radioactive by neutrons.

U. S. No. 2,989,635. S. A. Scherbatskoy. Iss. 6/20/61. App. 12/18/53, 8/1/57, and 4/8/58.

Method and Apparatus for Neutron Detection. A neutron spectrometer having a detector containing hydrogenous substance and producing an electrical impulse with each incident neutron, and three or more pulse-amplitude selective networks connected to the detector, with indicators connected to the networks in pairs to indicate the differences in counting rates between the respective networks.

U. S. No. 2,989,637. S. A. Scherbatskoy. Iss. 6/20/61. App. 4/26/57.

Spectrometer. A radiation spectrometer having a variable-gain amplifier between the detector and the pulse-height discriminator in order to obtain a pass band whose width varies in proportion to the mean height of the pass band.

U. S. No. 2,990,475. S. A. Scherbatskoy. Iss. 6/27/61. App. 9/28/55.

Determining the Proximity of a Radiation Source. A method of radioactivity prospecting in which the distance to a gamma-ray source is determined by using a detector connected to two pulse-height discriminators one of which is sensitive only to primary photons and the other sensitive only to Compton-degraded photons, measuring the ratio of counts, and comparing the ratio with a distance calibration curve for the intervening medium.

SEISMIC PROSPECTING

U. S. No. 2,982,371. J. P. Woods and T. Prickett, Jr. Iss. 5/2/61. App. 9/2/54. Assign. The Atlantic Refining Co.

Seismic Exploration Method and Apparatus. A variable-frequency seismic system using a motor-driven vibration generator and a distant geophone and also a

geophone near the generator, signal from the latter being delayed by a magnetic drum time-delay unit and used to control a synchronous relay, so that only those signals received by the distant geophone are recorded that have a chosen travel time.

U. S. No. 2,982,919. O. C. Montgomery. Iss. 5/2/61. App. 3/3/55. Assign. Phillips Petroleum Co.

Automatic Gain Control Amplifier and Seismic Amplifier System. A seismograph avc system in which signal from an oscillator is applied to the control channel through an adjustable impedance so that the control channel is blocked during the first arrivals and the oscillator signal subsequently reduced as a function of time to release the avc for operation on seismic signals.

U. S. No. 2,982,923. H. C. Hibbard. Iss. 5/2/61. App. 1/6/58. Assign. Jersey Production Research Co.

System of Seismic Recording. A seismograph recording system using a pulse-time-duration type of high-frequency carrier modulation by using a succession of short pulses of high-frequency carrier with the length of pulse varied from a standard zero-signal length by the amplitude of the seismic signal.

U. S. No. 2,982,940. R. A. Fryklund. Iss. 5/2/61. App. 3/13/56. Assign. Raytheon Co.

Echo-Ranging System. An echo sounding recorder having a stylus carried on a motor-driven endless belt that traverses an electrosensitive record paper with the transmitter keyed to emit a signal at an adjustable delay time after the stylus starts across the record, the delay being adjusted to vary the depth scale.

U. S. No. 2,982,941. M. E. Chun. Iss. 5/2/61. App. 7/17/50. Assign. U.S.A.

Directional Sound Apparatus. A sound direction-finding system using two receivers whose sum and difference signals are obtained and the sum signal amplified by an amplifier whose gain is controlled inversely as the amplitude of the difference signal.

U. S. No. 2,982,942. J. E. White. Iss. 5/2/61. App. 1/7/53. Assign. Socony Mobil Oil Co., Inc.

Directional Sound Detection. A system of sound field measurement using a pressure detector and three mutually perpendicular velocity detectors and multiplying the instantaneous pressure signal with each of the velocity components and displaying the vector sum of pairs of the products on c-r tube screens.

U. S. No. 2,983,901. L. C. Paslay, C. B. Brown, and N. N. Estes. Iss. 5/9/61. App. 4/16/45.

Crystal Hydrophone. A piezoelectric hydrophone containing a liquid separated from the sea water by a flexible diaphragm and in contact with the base of a conical baffle plate whose smaller end transmits the vibration forces to a stack of crystals.

U. S. No. 2,984,111. J. Kritz. Iss. 5/16/61. App. 6/19/59. Assign. American Bosh Arma Corp.

Accelerometer. An accelerometer in which the inertia mass is supported by flexure mode crystal tapes maintained in oscillation at a frequency depending on the tension exerted by the mass.

U. S. No. 2,984,801. N. C. Pflaum. Iss. 5/16/61. App. 4/30/59. Assign. Gulf Research & Development Co.

Filter Control Circuit. A control circuit for a band-pass filter circuit employing saturable-core reactors in which the control coils are in a bridge circuit with reverse current fed to the center of the bridge from a rectifier.

U. S. No. 2,984,819. L. N. Miller. Iss. 5/16/61. App. 7/14/44. Assign. U.S.A.

Magnetostrictive Transducer. A hydrophone having a plate to which one end of each of a number of vibrating magnetostrictive tubes are attached, the tubes being of different resonant frequencies to provide a wide resonance band.

U. S. No. 2,986,722. P. S. Williams. Iss. 5/30/61. App. 10/12/54. Assign. Jersey Production Research Co.

Recording and Reproducing Seismic Signals. A system of seismograph recording in which the geophone signals are recorded on a multi-track magnetic tape and the tracks subsequently played back in succession and recorded in variable-amplitude form by a pen recording on a drum on the same shaft as the tape and with the pen moved across the drum as the latter rotates so as to display the tracks in visually observable form.

U. S. No. 2,987,701. W. W. Grannemann. Iss. 6/6/61. App. 5/31/55. Assign. California Research Corp.

Methods and Apparatus for Eliminating Singing Components from Seismic Signals. A system for eliminating ringing by using a network that produces an auxiliary signal of the same frequency as the detector signal, and inverting the auxiliary signal and combining it with the original detector signal to cancel the ringing component.

U. S. No. 2,988,728. D. G. Marlow. Iss. 6/13/61. App. 7/6/53. Assign. United Geophysical Corp.

Piezoelectric Hydrophone. A deep-well geophone of the pressure-hydrophone type having a stack of piezoelectric quartz rings with intervening annular electrodes, one pole being brought out by a central conductor and the other pole by an external conductor, and with the azimuthal directions of maximum and minimum coefficient of thermal expansion of alternate

quartz rings arranged 90° apart to avoid shearing stresses.

U. S. No. 2,988,729. A. W. Musgrave. Iss. 6/13/61. App. 3/1/57. Assign. Socony Mobil Oil Co., Inc.

Production of Seismic Record Sections. A system of variable-amplitude seismic recording in which the traces are spaced in relation to the reflection-point spacing and the end trace which may be partially off the record is reproduced on the adjacent record so that the records may be laid down to give a record section without gaps between traces representing adjacent reflection points on different records.

U. S. No. 2,989,135. R. Pierce, Jr. and W. H. Cox. Iss. 6/20/61. App. 8/24/55. Assign. Sun Oil Co.

Method for Seismic Surveying. A system of reflection shooting using two detectors in a bore hole spaced so that the step-out for reflections is one-quarter wave length, reproducing the detector signals and introducing a time delay in one equal to the step-out and subtracting the two signals.

U. S. No. 2,989,596. B. D. Lee and A. L. Parrack. Iss. 6/20/61. App. 8/6/57. Assign. Texaco Inc.

Method and Apparatus for Obtaining Constant Speed Drive for Low Speed Recorders. A seismograph recorder in which the driving motor drives a high speed flywheel that is coupled to the recording drum and arranged so that mechanical vibrations of the coupling are outside the range of seismic frequencies.

U. S. No. 2,989,726. J. M. Crawford and W. E. N. Doty. Iss. 6/20/61. App. 4/28/54. Assign. Continental Oil Co.

Method of and Apparatus for Determining the Travel Time of a Vibration Signal between Spaced Points. A variable-frequency seismic prospecting system in which the geophone signal is multiplied by a delayed counterpart of the source signal and the product integrated, the multiplication and integration being made for various time delays to determine the delay that gives the maximum integration, the recording period being longer than the travel time plus the source program but shorter than the time required to cross-correlate so as to provide a ratio of at least two to one between signal and noise.

U. S. No. 2,989,869. G. J. Hanggi. Iss. 6/27/61. App. 2/25/57. Assign. Continental Oil Co.

Constant Force Variable Speed Vibrator. A constant force variable frequency vibrator having counter-rotating shafts carrying eccentric masses, and also having a radially movable mass held by a central spring possessing a variable spring rate so that the movable mass is positioned at a speed-dependent radius.

U. S. No. 2,990,535. D. B. Parkinson, W. C. Roberts, L. Haner, and A. E. Lepley. Iss. 6/27/61. App. 11/26/56. Assign. Clevite Corp.

Seismic Equipment. A seismograph magnetic recording-reproducing apparatus having two multi-channel drums and a single channel memory drum rotating in synchronism, each trace of the first drum being played back in succession, with fixed and variable corrections made in transferring the trace to the memory drum from which the corrected record is then transferred to the second multi-channel drum.

WELL LOGGING

U. S. No. 2,982,191. C. C. Laval, Jr. Iss. 5/2/61. App. 9/21/59.

Borehole Photographic Apparatus Providing Fluid Displacement. A borehole camera for use in photographing the upper end of a tool lost in the hole and having on its lower end a long inverted funnel which engages the end of the fish and which is filled with a transparent fluid through which the fish can be photographed.

U. S. No. 2,982,858. W. A. Hoyer and R. C. Rumble. Iss. 5/2/61. App. 3/23/59. Assign. Jersey Production Research Co.

Atomic Particle Generating Device. A neutron source for use in a borehole and having a tube separated into two compartments by a sintered glass plate with the gas in one compartment ionized by the r-f field of an external coil and ions that penetrate the porous plate to the other compartment accelerated by a pulsed high voltage to strike a target.

U. S. No. 2,983,586. A. Blanchard. Iss. 5/9/61. App. 11/7/57. Assign. Schlumberger Well Surveying Corp.

Borehole Testing Method and Apparatus. A system for chemically detecting hydrocarbons in the borehole wall and having a sonde that hydraulically forces a cup against the formation to isolate a region to which reduced pressure is applied to remove mud cake and then an oxidizing agent forced into the formation and the temperature change detected with a thermocouple.

U. S. No. 2,983,587. J. H. May and H. L. Mann, Jr. Iss. 5/9/61. App. 3/26/58. Assign. National Lead Co.

Gas Detection in Well Logging. A method of detecting methane in gas extracted from drilling mud by passing the gas over a catalyst that causes combustion of hydrogen and heavy hydrocarbons and subsequently detecting methane with a hot-wire gas detector.

U. S. No. 2,983,820. A. H. Frentrop. Iss. 5/9/61. App. 3/8/54. Assign. Schlumberger Well Surveying Corp.

Well Logging Apparatus. A neutron source for use in a borehole having an ion source that is excited by a radio-frequency field and has a probe opening through which ions escape to an accelerator containing a target at high

potential, the target being one electrode of an external electrolytic cell so that tritium in the target can be continuously replaced.

U. S. No. 2,984,781. H. F. Schwede. Iss. 5/16/61. App. 3/9/53. Assign. Schlumberger Well Surveying Corp.

Apparatus for the Nondestructive Testing of Materials. A paramagnetic resonance logging system in which the earth's magnetic field is modulated by a coil connected to a low-frequency oscillator and the absorption of a high-frequency alternating magnetic field is measured, the sonde including a sample of material containing the free radical tris-para-nitrophenyl methyl to provide a reference signal.

U. S. No. 2,985,760. A. J. Gale. Iss. 5/23/61. App. 9/12/58. Assign. High Voltage Engineering Corp.

Compact Neutron Source. A neutron source for use in a borehole and having two belt-type electrostatic generators, one of which charges the positive-ion source at a positive voltage and the other charges the target at a negative voltage, so that the radial voltage to ground is but half the total accelerating voltage.

U. S. No. 2,985,822. H. W. Georgi. Iss. 5/23/61. App. 9/16/57. Assign. Well Surveys, Inc.

Modulation System for Casing Collar Locators. A signalling system for a well tool having a magnetic amplifier whose control winding is connected to the signal source and whose reactive winding is used to modulate a carrier that is fed to the surface, the amplifier having a resistor connected to its reactive windings so as to provide feedback that is positive only for signals of one polarity.

U. S. No. 2,986,639. V. A. Josendal and R. J. Stegemeier. Iss. 5/30/61. App. 4/25/57. Assign. Union Oil Co. of Calif.

Groundwater Direction Determination. A method of determining the azimuthal direction of fluid flow in a formation penetrated by a borehole by placing a source of radiation in the center of the hole in a permeable material containing a radiation-absorbing fluid and a number of radiation detectors in various azimuths so that transverse movement of the absorbing fluid can be observed.

U. S. No. 2,986,693. R. L. Alder. Iss. 5/30/61. App. 1/21/58. Assign. Dresser Industries, Inc.

Electrical Logging System. A system for obtaining a plurality of resistivity curves on a time-sharing basis by connecting different electrodes in successive arrangements by means of relays in the sonde controlled by a programming switch at the surface.

U. S. No. 2,986,694. F. L. Stricklin, Jr. Iss. 5/30/61. App. 7/11/56. Assign. Shell Oil Co.

Apparatus for Exploring Drill Holes. A sonde for electrically contacting the wall of a dry hole having a reservoir of conductive liquid in an insulated housing with a horizontal discharge nozzle through which a stream of liquid is discharged to the borehole wall, and an electrode in the bottom of the reservoir connected to the cable.

U. S. No. 2,986,695. F. E. Buell. Iss. 5/30/61. App. 11/13/56. Assign. Shell Oil Co.

Electrical Well Logging Apparatus. A sonde for electrically contacting the wall of a dry hole having a reservoir of conductive liquid and a valve actuated by fingers that frictionally engage the borehole wall, downward motion of the sonde keeping the valve closed and upward motion opening the valve to discharge a fine stream of liquid that strikes the borehole wall.

U. S. No. 2,987,668. M. Gondouin. Iss. 6/6/61. App. 5/29/56. Assign. Schlumberger Well Surveying Corp.

Systems for Well Logging. An electromagnetic formation logging system having a pair of coaxial toroidal coils with a common passage to which conducting well fluid has access, the coils being pressed flat against the borehole wall and one coil excited with a-c and the signal induced in the other coil compared with that in the first coil by a phase-sensitive detector.

U. S. No. 2,987,822. J. J. Arps. Iss. 6/13/61. App. 2/1/52, 12/26/56, and 9/17/57.

Depth Measurement. Apparatus for measuring the length of pipe in a well having under the rotary table a pair of rollers that bear against the pipe and actuate a signal generator connected to oppositely arranged one-way clutches on a footage counter.

U. S. No. 2,987,823. H. Boucher. Iss. 6/13/61. App. 5/12/59.

Measuring Device. A drilling footage recorder having a line that passes around a drum on a shaft with a cam that actuates the recording pen, and a hydraulically controlled clutch connecting the drum to the shaft.

U. S. No. 2,988,642. S. Soloway. Iss. 6/13/61. App. 6/30/58. Assign. Schlumberger Well Surveying Corp.

Particle Accelerating System. A borehole accelerator having an envelope containing an ionizable gas and electrodes between which an ion-producing discharge is periodically effected by a d-c pulser, and with an a-c voltage applied between an electrode having an ion-emitting aperture and a target, the pulser being operated at the peak of the a-c voltage applied to the target.

U. S. No. 2,988,671. W. R. Arnold. Iss. 6/13/61. App. 6/30/58. Assign. Schlumberger Well Surveying Corp.

Particle Accelerating System. A borehole accelerator having an envelope containing an ionizable gas and

having an ion source section and an ion accelerating section, an a-c accelerating potential being applied to the target and to an external capacitative electrode through an integral diode rectifier, and the ion source energized in synchronism with the a-c accelerating potential.

U. S. No. 2,988,692. F. H. Mann. Iss. 6/13/61. App. 9/27/55 and 9/12/56. Assign. Schlumberger Well Surveying Corp.

Apparatus for Exploring Boreholes. A sonde for an electrical dipmeter having an elongated electrode carrying at least three small azimuthally spaced insulated electrodes at the same potential and whose currents are focussed, the separate currents to the small electrodes being measured by using a remote controlled stepping relay, the sonde also containing a photographic inclinometer.

U. S. No. 2,989,631. F. O. Bohn. Iss. 6/20/61. App. 7/23/58. Assign. Lane-Wells Co.

Tracer Injector and Detector. A well sonde for injecting into the well fluid discrete quantities of radioactive tracer by explosively fracturing a vial of the material and having a detector that senses passage of the tracer immediately after it is released into the well fluid.

U. S. No. 2,990,474. S. A. Scherbatskoy. Iss. 6/27/61. App. 1/25/54.

Radiation Detector. A gamma-ray logging system in which the sonde has two or more gamma-ray counters in a plane transverse to the axis of the sonde, the counters being shielded from charged particles and connected to a coincidence circuit to count only horizontally directed gamma rays from the formation.

MISCELLANEOUS

U. S. No. 2,986,732. C. E. Marshburn. Iss. 5/30/61. App. 3/26/56. Assign. U.S.A.

Navigation System. A phase-comparison type of radio position determining system using three transmitters from which two sets of hyperbolic position lines are set up, and two reference stations respectively located midway between the main stations that alternately transmit a different frequency related to the sum of the modulation components of the main stations.

U. S. No. 2,988,640. F. E. Steele. Iss. 6/13/61. App. 8/7/53.

Method Relating to the Production of Oil. A method of determining whether a well pump is pumping off all of the fluid that enters the well by introducing on top of the fluid column in the well a radioactive material in a light oil and detecting presence of radioactivity in the well flow line.

U. S. No. 2,989,234. R. B. Stelzer. Iss. 6/20/61. App. 7/30/56. Assign. Texaco Inc.

Electrical Analogue. A potentiometric model of a radial system having a cylindrical pool of electrolyte simulating the borehole, and successive annular segments of increasing radius subtending different central angles to represent the invaded zone and unaltered formation.

SELECTED LIST OF U. S. PATENTS ISSUED DURING MAY AND JUNE OF 1961

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,982,003	224	2,982,917	308	2,983,518	484
2,982,122	380	2,982,919[a]	372	2,983,586[a]	172
2,982,127	428	2,982,923[a]	360	2,983,587[a]	252
2,982,130	392	2,982,940[a]	108	2,983,654	324
2,982,135	148	2,982,941[a]	12	2,983,790	12
2,982,138–140	16	2,982,942[a]	12, 360	2,983,794	224
2,982,167	444	2,982,954–956	316	2,983,796	484
2,982,191[a]	280	2,982,958	312	2,983,817[a]	308
2,982,371[a]	360	2,983,140	428	2,983,818[a]	308
2,982,488–489	224	2,983,146	288	2,983,819	308
2,982,821	12, 224	2,983,149	4	2,983,820[a]	304
2,982,855	308	2,983,150–151	16	2,983,865[a]	232
2,982,856	196	2,983,277	16	2,983,866	68
2,982,858[a]	308	2,983,442–443	68	2,983,901[a]	436, 484
2,982,895	200	2,983,448	68	2,983,916	316
2,982,910	344	2,983,457	224	2,983,988	484
2,982,912	140	2,983,460	224	2,984,097	168

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	*Subject**
2,984,098	12
2,984,102–103	428
2,984,110	492
2,984,111[a]	4
2,984,114	16
2,984,146	420
2,984,148	200
2,984,149	196
2,984,352	308
2,984,414	68
2,984,535–537	324
2,984,538	224
2,984,627	196
2,984,709	224
2,984,711	484
2,984,741	316
2,984,745[a]	304, 308
2,984,746	308
2,984,748	308
2,984,756	12
2,984,781[a]	220, 228
2,984,782	228
2,984,783[a]	232
2,984,800	12
2,984,801[a]	348
2,984,803	288
2,984,819[a]	436, 484
2,984,833	316
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2,985,012–013	16, 288
2,985,014	148
2,985,016	324, 460
2,985,018	288, 444
2,985,019–020	288
2,985,021	4
2,985,022–023	16
2,985,026	68
2,985,045	308
2,985,181	68
2,985,182	484
2,985,194	288
2,985,290	224
2,985,300	228
2,985,371–372	68
2,985,373	16, 68
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2,985,499	324
2,985,593	308
2,985,713	224
2,985,723	224
2,985,728	324
2,985,757	484
2,985,758	308
2,985,759	196
2,985,760[a]	304, 308
2,985,785[a]	308
2,985,822[a]	220, 516
2,985,823	492
2,985,824	228
2,985,826	116
2,985,827	188
2,986,033	16
2,986,034	196
2,986,036[a]	180
2,986,038	288
2,986,089	48
2,986,090	136
2,986,151	148
2,986,227	12
2,986,318	224
2,986,333	68
2,986,441	308
2,986,442–443	324
2,986,527	196
2,986,601	324
2,986,606	324
2,986,607–609	224
2,986,615	4
2,986,633	196
2,986,635[a]	308
2,986,636[a]	308
2,986,637	196
2,986,638[a]	308
2,986,639[a]	304
2,986,640[a]	308
2,986,641	308
2,986,693[a]	116
2,986,694[a]	116
2,986,695[a]	116
2,986,704	68
2,986,715	288
2,986,717	196
2,986,722[a]	364
2,986,726–728	68
2,986,729	16
2,986,730–731	316
2,986,732[a]	312
2,986,890	460
2,986,921	380
2,986,922	428
2,986,925	496
2,986,931–932	428
2,986,933	16
2,986,938	288
2,986,941–946	16
2,987,233	224
2,987,248	16, 68
2,987,254	16, 68
2,987,255	68
2,987,264	224
2,987,269	316
2,987,273–277	16
2,987,367	324
2,987,488	308
2,987,581–583	224
2,987,618	236
2,987,620	416
2,987,621	308
2,987,622	196
2,987,634	68
2,987,668[a]	128
2,987,669	484
2,987,687	288
2,987,698	108, 316
2,987,700	484
2,987,701[a]	360
2,987,716	68
2,987,719–720	316
2,987,822[a]	520
2,987,823[a]	100, 520
2,987,911	148
2,987,915	148
2,987,916	200
2,987,918	188
2,987,920	288
2,987,923	496
2,987,927	180
2,987,929	324
2,987,951	136
2,987,997	136
2,988,270	68
2,988,294–295	224
2,988,366	484
2,988,415	324
2,988,522–523	308
2,988,604	224
2,988,639[a]	308
2,988,640[a]	304
2,988,642[a]	304, 308
2,988,643	68
2,988,671[a]	304, 308
2,988,690[a]	124
2,988,691[a]	124
2,988,692[a]	116
2,988,717	460
2,988,719	180
2,988,728[a]	376, 484
2,988,729[a]	352
2,988,736	224
2,988,737	68
2,988,739	316
2,988,816	16
2,988,818	16
2,988,821	16
2,988,914	496
2,988,916	148

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,988,920	4	2,989,631[a]	304, 308	2,989,868	68
2,988,921	428	2,989,633	308	2,989,869[a]	76
2,988,923	16	2,989,635[a]	308	2,990,116	68
2,988,952–953	444	2,989,637[a]	308	2,990,182	324
2,988,993–994	48	2,989,638	196	2,990,184	324
2,989,051	324	2,989,642	68	2,990,221–222	16
2,989,135[a]	356, 360	2,989,643	196	2,990,453	12
2,989,179	228	2,989,662	308	2,990,455	224
2,989,234[a]	68	2,989,672	16	2,990,474[a]	304
2,989,238–239	68	2,989,697	324	2,990,475[a]	308
2,989,270	16, 68	2,989,711	484	2,990,476	308
2,989,357	324	2,989,725	484	2,990,482	200
2,989,415	224	2,989,726[a]	76	2,990,512	228
2,989,594–595	224	2,989,742–743	316	2,990,513[a]	232
2,989,596[a]	224, 324, 364	2,989,864	140	2,990,535[a]	352
2,989,597	484	2,989,866	148	2,990,543	200

CONTRIBUTORS

WILLIAM MANSFIELD ADAMS

DEWITT CLINTON ALLEN

WILLIAM MANSFIELD ADAMS obtained a B.A. from the University of Chicago, a B.A. in geophysics from the University of California, and a M.S. and Ph.D. in geophysics and geophysical engineering from St. Louis University. Assistantships and a Gulf R&D Fellowship provided financial support. After a summer at the Dominion Observatory of Canada, he received a Fulbright Grant to study for a year in Italy. He has done seismological exploration for Shell Oil, Stanolind, Western Geophysical, and The Geotechnical Corporation. He is now with the University of California Lawrence Radiation Laboratory as a Deputy Technical Director for the AEC Measurements Program on Project DRIBBLE. He holds membership in SEG, EAEG, Seismological Society of America, AGU, Geological Society of America, and others.

DEWITT CLINTON ALLEN received his bachelors degree in Physics in 1937 from the University of California at Berkeley and his masters in Meteorology in 1943 from the California Institute of Technology at Pasadena. Four and a half years of military service during WW II included duty in the Pacific as a weather officer with the Army Air Corps and led to a period of employment by Pan American World Airways on the air routes through Hawaii. Mr. Allen spent the Korean War at Honolulu International Airport as a senior aircraft dispatcher for contract airlines flying the airlift; he also held an Air Force Reserve assignment at Hickam Field. Since 1954, Mr. Allen has been employed by the University of California's Lawrence Radiation Laboratory at Livermore, California. He has done research in the fields of Meteorology and Seismology and participated in nuclear test operations. His scientific affiliations include the Northern California Branch of the American Meteorological Society, the Seismological Society of America, and the American Geophysical Union.

MARGARET E. BOWER attended the University of Alberta and graduated in 1949 with the degree of B.Sc. in Mathematics. In 1950, Miss Bower joined the staff of the Geophysics Division, Geological Survey of Canada, Ottawa. She was employed in the Airborne Magnetometer Section and was supervisor of aeromagnetic compilation from 1953 to 1957. Following this, she worked on aeromagnetic interpretation and on special projects. At present, she is engaged in compiling and interpreting the data from sea magnetometer surveys.

T. Y. CHANG was born in Canton, China and became a U. S. citizen in 1953. Immediately following graduation from the University of Colorado in 1942 with a B.S. degree in Electrical Engineering he was employed by National Geophysical Company as a member of a seismic field crew. He joined the Atlantic Refining Company's Geophysical Section in 1944. In 1947 he attended Columbia University. After receiving a M.S. degree in Industrial Engineering from Columbia, he returned to work for Atlantic. His work has been in seismic review interpretation. At present he is the head of a seismic review team of the Atlantic Refining Company.

T. Y. Chang

Mr. Chang is a member of the SEG, the Houston Geophysical Society, the Houston Chapter of A.P.I., and Pi Mu Epsilon.

John N. Dahm

John N. Dahm received a B.A. Degree in 1943 from the University of Wisconsin and did graduate work at Oklahoma University in 1948–1949.

Mr. Dahm was engaged 14½ years in petroleum exploration, one and a half years in uranium exploration, and one year as an instructor at Texas A&M. He is presently Senior Geologist for El Paso Natural Gas Company.

Mr. Dahm is a member of AAPG, IAPG, and AIME.

John H. Earl served in the U. S. Army in Europe during World War II. He attended Kansas State College from 1945 to 1948 and received a B.S. Degree in 1948.

Mr. Earl was employed by GSI from 1948 to 1951 as a Computor and Party Chief. In 1951, he became Party Chief and Interpretation Supervisor, Gulf Coast and Rocky Mountain region, for Gulf Oil Corporation. He joined El Paso Natural Gas Company in 1956 as Geophysicist and is Chief Geophysicist at present.

John H. Earl

Mr. Earl is a member of SEG, AAPG, Seismological Society of America, and Sigma Gamma Epsilon.

Alan F. Gregory is a geologist with the Geophysics Division of the Geological Survey of Canada, Ottawa. He is a graduate of the University of Toronto (B.A., 1950) and the University of Wisconsin (Ph.D., 1958). He was active in the development of aeroradiometric survey techniques in Canada and, prior to joining the staff of the Geological Survey, held senior exploration posts in several mining companies. Dr. Gregory is a Fellow of the Geological Association of Canada, a member of the Professional Engineers of the Province of Ontario, and a member of the Ottawa Geophysical Discussion Group.

L. V. Hawkins

L. V. Hawkins obtained his B.Sc degree from the University of Sydney, Australia, in 1950 and held a

post-graduate research demonstratorship in the Department of Geology and Geophysics during 1951 and 1952. He was a geophysicist with the Bureau of Mineral Resources, Australia, from 1953 to 1958 and has been lecturer in geophysics at the University of New South Wales since 1958. He obtained his M.Sc degree from the University of Sydney in 1960, and is a member of the Geological Society of London (F.G.S.), SEG, AGU, and EAEG.

ELIZABETH R. KING

ELIZABETH R. KING graduated from Smith College in 1947 with a B.A. in geology, and subsequently studied physics at American University. She has been employed by the U. S. Geological Survey from 1948 to the present as a geologist and exploration geophysicist specializing in the interpretation of aeromagnetic data. She is a member of SEG, AGU, and the Geological Society of Washington.

L. W. MORLEY received his B.A. degree in Physics and Geology from the University of Toronto in 1946 after interrupting his university work to serve as a radar officer with the British Navy. He was employed by Fairchild Aerial Surveys from 1946 to 1948 and was party chief when they pioneered, with Gulf Research, in a combined Shoran-controlled photographic and aeromagnetic survey in Venezuela and Colombia. Returning to Toronto in 1948, he acted as chief mining geophysicist with the Dominion Gulf Company until 1949 when he began graduate work at the University of Toronto. In 1952 he obtained his Ph.D. in Geophysics with a thesis on rock magnetism. Since 1952, Dr. Morley has been chief of the Geophysics Division, Geological Survey of Canada where he has been active in initiating geophysical research and in organizing an aeromagnetic survey of the Canadian Shield. He is a member of the SEG, the AGU, the Professional Engineers of the Province of Ontario, and the Canadian Institute of Mining and Metallurgy.

ALBERT W. MUSGRAVE

ALBERT W. MUSGRAVE spent two years in the Navy as a radio technician before his graduation from the Colorado School of Mines in 1947 with a degree in geological engineering (geophysics option). After spending three years on a field seismic crew with the Magnolia Petroleum Company, where he advanced to the position of seismologist, he returned to the Colorado School of Mines for advanced work. On a Magnolia Fellowship he obtained the degree of Doctor of Science in Geophysics in 1952 and returned to work with the Magnolia Petroleum Company as a seismic party chief. His thesis, "Wavefront Charts and Raypath Plotters," was later published as a quarterly of the Colorado School of Mines.

He and his co-authors received the Best Paper Award for 1958 from GEOPHYSICS for "Directivity Effect of Elongated Charges." He also co-authored "Outlining of Salt Masses by Refraction Methods," published in GEOPHYSICS February, 1960.

In 1954, he was made research geophysicist attached to the Dallas Office of the Magnolia Petroleum Company. His work consisted of applied research on special seismic problems in velocity surveying, refraction profiling, and reflection interpretation.

March, 1960, he was changed to Superintendent of Special Problems in the Geophysical Services of Mobil Oil Company where he is responsible for magnetic tape playback operations and special interpretation problems for Mobil Oil Company and Mobil International Company.

He is a member of the SEG, AAPG, EAEG, Tau Beta Pi Society, and the Research Engineering Society of America. In 1957, he was second vice-president of the Dallas Geophysical Society and a member of the Joint Geological and Geophysical Committee on Public Information. In 1958, he was appointed first vice-president of the Dallas Geophysical Society to fill an unexpired term. He is presently Chairman of the Distinguished Lecture Committee for the SEG, and has

been appointed Editor of the SEG's special Refraction Volume.

DONALD R. OKSA

DONALD R. OKSA received the Associate of Arts degree from Gogebic Junior College and the B.S. in Geological Engineering from the Michigan College of Mining and Technology. He served in the Air Force from 1943 to 1946 in flight and maintenance engineering. He was employed by the Atlantic Refining Company in 1947, and in 1951 he joined the Sinclair Oil and Gas Company. With Sinclair, Mr. Oksa was first in the Land Department, but in 1952 was transferred to the Research Section and has been engaged in seismic interpretation problems.

Mr. Oksa is a member of SEG and Geophysical Society of Tulsa.

NED A. OSTENSO

NED A. OSTENSO received his B.S. degree in geology in 1952 and M.S. degree in geology and geophysics in 1953, both from the University of Wisconsin. From 1953 to 1955 he served in the U. S. Army Signal Corps as Meteorology Project Officer at the Army Arctic Center, Alaska. During this time he conducted gravity surveys in Alaska and the Canadian northwest. In 1956, he participated in a geophysical expedition in Greenland, conducted by Columbia University, following which he joined the IGY Antarctic program as a geophysicist on the Byrd Station traverse party, returning to the University of Wisconsin in 1958. Mr. Ostenso then spent the austral summer of 1958–59 as a member of the airborne traverse party in West Antarctica followed by four months in establishing pendulum gravity stations in Africa and Europe. Mr. Ostenso is currently employed as a project associate at the University of Wisconsin, where he is on the staff of the Geophysical and Polar Research Center and completing work on a Ph.D. degree.

HARRY R. STENSON

HARRY R. STENSON graduated from the University of Texas in 1949 with a B.S. Degree in Geology. He gained his first geophysical experience in 1942 working with a contract geophysical company in West Texas. He served three years with the 650th Engineers during World War II. After graduation, Mr. Stenson worked with contract geophysical companies in Texas, Louisiana and Mexico in the capacity of computer, party chief and seismologist. Since 1954 he has been with Creole Petroleum Corporation in Caracas, Venezuela. His present position is Senior Seismic Interpreter.

Mr. Stenson is a member of the SEG, AAPG, AAAS, and the Texas Academy of Science.

EDWARD THIEL received his B.S. degree in physics in 1950 from the University of Wisconsin. During 1952–53 he served as Lieutenant in the U. S. Air Force. In 1955, he was awarded the Ph.D. in geology by the University of Wisconsin, presenting a dissertation on the "mid-continent gravity high" which extends from Lake Superior southwestward to Kansas. He was subsequently post doctoral research fellow at the University of Utah and geophysicist with the American Geograph-

EDWARD THIEL

ical Society's glaciological research program on the Juneau Ice Field, Alaska. During the IGY Dr. Thiel was Chief Seismologist with the Arctic Institute of North America and co-leader of the Filchner Ice Shelf oversnow traverse in Antarctica. Following the IGY he returned to the University of Wisconsin as Principal Investigator, together with Dr. C. R. Bentley and Prof. G. P. Woollard, for the United States Oversnow Traverse Program in Antarctica. During this time he spent two austral summers as Chief Scientist for Antarctica airborne geophysical operations. Dr. Thiel is currently Assistant Professor of Geophysics at the University of Minnesota.

ALAN W. TROREY received his B.A.Sc. in engineering physics from the University of British Columbia in 1949. After engaging in microwave research at the Canadian National Research Council, he received M.S. and Ph.D. degrees in electrical engineering from Stanford University.

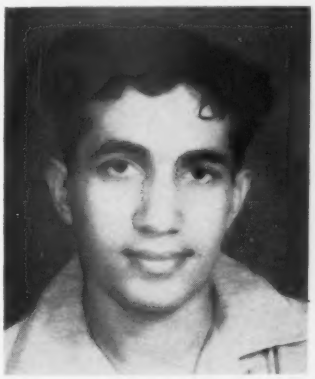
During his graduate work, Dr. Trorey conducted research in connection with low-frequency loran, information theory, and the plastic deformation of building structures.

In 1954, Dr. Trorey was employed by the California Research Corporation where he now holds the position of Senior Research Physicist. He has been concerned with the design of special-purpose seismic instrumentation and with various problems in theoretical and applied exploration seismology.

Dr. Trorey is a member of the American Association for the Advancement of Science and the Society of Sigma Xi.

ALAN W. TROREY

The following item was omitted from the October issue of GEOPHYSICS.



JANARDAN G. NEGI

JANARDAN G. NEGI was born in 1936. He received a B.Sc. degree in 1956 and a M.Sc. degree in 1958, both from Agra University, India. The undergraduate fields of study were Physics, Chemistry and Mathematics and the Master's degree was in Physics with a specialization in Electronics. He taught Physics at Holker College Indore to undergraduate and post-graduate classes for the academic session 1958–59.

Mr. Negi is presently working for a Ph.D. degree in Geophysics at Indian Institute of Technology, Kharagpur where he has held the Council of Scientific and Industrial Research Fellowship.

A biography of Pierre L. Goupillaud appears in GEOPHYSICS, v. 23, p. 378.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with By-laws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

James Wesley Adams (John W. Bolinger, C. C. Mason, S. A. Teasley, D. H. Miller)

Charles E. Curtis (Kalman N. Isaacs, Homer Jensen, Roger H. Pemberton, John Whitaker)

Philip H. Halstead (M. H. Lea, J. W. James, A. P. Marsh, N. Van Der Sleen)

W. W. Kleinecke (C. W. Payne, K. J. Warren, B. B. Robinson, Jr., W. F. Ashburn)

Milford Ray Lee (John Crawford, W. E. N. Doty, K. H. Waters, Frank Searcy)

Burton Merchant (C. W. Penny, John Healy, N. C. Born)

H. C. Miller, Jr. (K. G. McCann, J. E. Froelich, Jr., A. H. Petues, Jr.)

Frank W. Schmechel (Fielding L. Mitchell, Sam J. Dallison, Joe T. Williams, Kenneth H. Koenen)

Robert M. Trapp (B. F. Owings, Jr., R. M. Pinson, Ralph G. Anderson, L. D. Dawson)

Arthur W. Walzel (C. K. Fielder, B. M. Sellers, George P. Montgomery, J. R. Hughes)

George A. Winfrey (W. N. Farmer, J. E. Barthelemy, W. T. Brooks, J. W. Mathews)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Wm. E. N. Doty (John M. Crawford, Frank L. Searcy, K. H. Waters, Graydon L. Brown)

John F. Fox (J. C. Peffer, J. C. Menefee, W. L. Fellows, P. R. Letourneau)

Alister A. Lee (R. J. McCaffrey, J. L. Robinson, A. C. Armstrong)

Joseph B. Prendergast (F. C. McConnell, P. J. Farrell, J. A. C. Keefe)

Joe G. Saltamachia (Aart deJong, M. H. Dingman, W. T. Buckingham)

Robert V. Smith (W. P. Scaife, J. S. Rhodes, F. Uhrig, K. D. Huckabee)

Frank P. Sonnenbert (Paul D. Balbin, Charles W. Nicholls, Charles W. Hyatt, A. L. Sterr)

Maurice Eugene Taylor (Sigmund Hammer, E. K. Darby, Loyal D. Palmer, L. W. Gardner)

John D. Waskom (S. R. Marsh, E. L. Tomlin, E. J. Laurent, P. M. Tucker)

Marshall C. Wicker (J. S. Rhodes, K. D. Huckabee, A. E. Richmond, J. W. Miller)

ANNOUNCEMENTS

"The remaining issues of this editorship are completed. Consequently, *new manuscripts* should be sent to the editor elect, R. B. Rice, The Ohio Oil Company, P.O. Box 269, Littleton, Colorado.

The Editor"

ASME FORMS UNDERWATER TECHNOLOGY GROUP

Mr. Richard Neuendorffer, Chairman, ASME Professional Group on Underwater Technology, in a letter to the Editor, said "First, we should like to inform you of the existence of the Professional Group on Underwater Technology of the American Society of Mechanical Engineers. The objectives of this Group will be to promote the art and science of mechanical engineering in underwater technology and to encourage the preparation and publication of papers on engineering developments in this field.

Because of the breadth and depth in this field of activity, we are certainly aware of the interest that your own Society has in this area and therefore the second purpose of this letter is to indicate to you our willingness, and even enthusiasm, for joining forces with you in the furtherance of our mutual objectives. We hope, for example, that it may prove feasible to co-sponsor technical meetings with your organization and that we shall always feel free to exchange information with you and with members of your Society. If we can ever be of any assistance to your organization, I hope that you will feel free to call upon us."

JOINT EXECUTIVE COMMITTEE MEETING

The incoming and outgoing officers of the SEG met at SEG Headquarters in Tulsa on August 4, 1961. This meeting gave the incoming officers the opportunity to familiarize themselves with the duties they were to as

Sitting (left to right): L. Y. Faust, incoming President; J. P. Woods, outgoing President; and T. O. Hall, outgoing Past-President. Standing (left to right): F. A. Hale, outgoing Secretary-Treasurer; R. C. Kendall, outgoing Vice-President; M. B. Dobrin, incoming First Vice-President; R. B. Rice, incoming Editor; R. M. Pinson, incoming Secretary-Treasurer; and J. C. Hollister, outgoing First Vice-President. Outgoing Editor, N. C. Steenland and incoming Vice-President, S. H. Ward were unable to attend the meeting.

sume at the close of the Thirty-First Annual Meeting in Denver. The purpose of the Joint Executive Committee Meeting is to help bring about a smooth transfer of administrative responsibilities of the Society.

SEG FOUNDATION SCHOLARSHIPS

ROBERT J. MATHIESON, WILLIAM HUNG KAN LEE, and DAVID JACKSON have received scholarships from the Society of Exploration Geophysicists Foundation, according to Maynard W. Harding, Chairman of Scholarship Administration for the Foundation. Mathieson will be a graduate student at the University of Tulsa where he is studying toward a career in geophysics. He graduated from Will Rogers Senior High School in 1957 and from the University of Tulsa in 1960. He is the son of Mr. and Mrs. Raymond L. Mathieson.

Mathieson's scholarship was made possible by a grant from the George E. Failing Company to the SEG Foundation.

Lee, the son of Mr. and Mrs. H. Y. Lee, Edmonton, Alberta, will be in his final year at the University of Alberta. He will be studying geology and physics with honors standing. His scholarship was made possible by contributions from companies engaged in the oil exploration industry and from members of the Society of Exploration Geophysicists.

Jackson, who will major in geophysics at Cal Tech, belonged to the National Honor Society, the National Forensics League and the California Scholarship Federation while in high school in addition to participating in gymnastics, football, handball, baseball, and swimming. He received varsity letters in gymnastics. His scholarship for $1,000 came from a grant by the Independent Exploration Company of Houston, long-time member of the Foundation's Scholarship Program.

In the summer of 1960 Jackson was awarded a scholarship by the National Science Foundation to attend a six-weeks program in chemistry and geology at the Colorado School of Mines.

Awards from the SEG Foundation are made as scholarships to outstanding students majoring in fields of interest to petroleum exploration, and as grants-in-aid for teaching and research. The Foundation's trust fund is made up of contributions from organizations and individuals interested in the earth sciences.

Houston Geophysical Society Supports Houston Museum of Natural Science

The Geophysical Society of Houston has approved a gift of $1,000 to the new Houston Museum of Natural Science. This sum will be contributed to the Building Fund of the Museum at such time as it may be needed for construction purposes.

The proposed new Museum will have as its primary purpose the provision of a fully representative science center, including both natural science and natural history, for the Houston community.

Palmer Hutcheson, Jr., president of the Houston Museum of Natural Science, expressed the appreciation of the Board of Trustees and members for this tangible evidence of support for the Museum.

Mr. T. I. HARKINS, President of Independent Exploration Company is pleased to announce the recall from retirement of DR. F. M. KANNENSTINE, in the capacity of Director of Development and Production on the "Stomper" (weight-dropping) program. In this capacity he has established a shop drafting department and is organizing and standardizing shop procedure. The Company feels it is quite fortunate in obtaining his services at this time.

In 1937, Dr. Kannenstine established Kannenstine Laboratories as an affiliate of Independent Exploration Company designing and building geophysical equipment. He disbanded Kannenstine Laboratories and retired in December, 1953 due to ill health.

His background in the design and building of geophysical equipment over a period of 35 years is impressive. He received his Ph.D. in Physics from the University of Chicago in 1922 and was research instructor at that University under Professor Michelson. He resigned this position in 1925 to become director of the research laboratory designing and building seismograph equipment for the newly organized Geophysical Research Corporation.

He remained in this capacity until the organization of Independent Exploration Company in 1932, at which time he became Vice-President in charge of Research for Rosaire and Kannenstine, designing and building instruments for the Independent Exploration Company.

Dr. Kannenstine is a member and past president (1938–39) of the Society of Exploration Geophysicists, Fellow of the American Association for the Advancement of Science, Fellow of the Physical Society, Member of the Optical Society, Member of American Geophysical Union, Associate Member of the Institute of Radio Engineers and Member of the Society of American Military Engineers.

ABSTRACTS

Bulletin (Izvestiya) April, 1961, Academy of Sciences, USSR, Geophysics Series

The Use of Modeling to Solve a Converse Problem of Magnetic Prospecting (The Shchigry anomaly of the KMA)

A. G. KALASHNIKOV

The possibility of using experimental methods to interpret observations in magnetic prospecting is demonstrated from modeling of the Shchigry magnetic anomaly of the KMA.

Numerical Methods of Calculating the Analytic Continuation of Potential Fields. II

V. N. STRAKHOV

A method is described of improving the accuracy of the approximate values obtained with the formulas of part 1 for the potential function in the region between the surface of the earth and the singularities of the function.

On a Quantitative Measure of the Information Acquired by Airborne Electromagnetic Prospecting Methods

YU. B. SCHAUB

It is shown that a single measure can be used to estimate the amount of information acquired by different airborne electromagnetic prospecting methods. A conducting sphere is used as an example in comparing the four principal survey methods—induction, an infinitely long cable, a rotating magnetic field, and measurement of the angle of inclination of the polarization plane of the earth's natural alternating magnetic field.

On the Solution of the Inverse Problem in γ-Ray Measurements

I. D. SAVINSKI

The problem of using γ-ray measurements to determine the density distribution of radioactive sources is discussed. A method is proposed for investigating possible ways of solving this inverse problem. The method is applicable in principle to practically any distribution of radioactive matter.

On the Thermal Field in Old Shields

S. A. KRASKOVSKI

Some Results of a Detailed Study of Seismic Conditions in the Stalinabad Region in 1955–1959

V. I. BUNÉ

This article presents the results of a study of the connection between the foci of earthquakes and the basic fractures, compares the parameters of the seismic conditions determined by short and long observations, and gives a comparison between the maps of seismic activity and maps of the isoseists according to macroseismic data.

Frequency Selection of Ocean Storm Microseisms

F. I. MONAKHOV

The Relation Between the Frequency Characteristics of Discrete and Continuous Groups

L. V. PETROV

A new expression is obtained for the frequency characteristic of a discrete group, in terms of the frequency characteristics of the generating continuous group. This expression is suitable for groups consisting of an even number of receivers.

It is shown that the frequency characteristics of triangular groups selected from an even number of recivers have, for all frequencies, absolute values that are not greater than those of the characteristics of groups taken from an odd number of receivers, if the original frequency characteristic for the continuous group corresponds to the interval between the seismographs.

Results of Electromagnetic Soundings in the Central Region of the Dnepr-Donets Depression

N. V. LIPSKAYA, N. A. DENISKIN AND YU. M. EGOROV

In 1959 the Department of Electrometry, Institute of Physics of the Earth, USSR Academy of Sciences, undertook work on methods of studying microvariations of the natural electromagnetic field within a frequency range of 0.005 to 1 cps. The aim was to verify theoretical propositions on the possibility of using the impedance of the earth's electromagnetic field in geoelectric-section charting of the earth's crust.

On Instrumental Determination of the Energy of Seismic Waves

V. D. Feofilaktov

On the Use of Variations of a Geomagnetic Field for Determining the Magnetic Susceptibility of Strongly-Magnetic Rocks in situ

M. I. Lapina

Magnetic Stability of Remanent Magnetization in Rocks with Two Ferromagnetic Components

S. Yu. Brodskaya

The Effect of Nonuniform Intensity of Magnetization of a Body of Constant Susceptibility on the Interpretation of Magnetic Anomalies by Simple Methods

V. M. Devitsyn, M. I. Lapina and B. L. Schneerson

A Rational Analyzer for a Frequency Storage and Conversion System

Yu. V. Khomenyuk

A Study of the Shear Modulus for Samples of Rocks under High Confining Pressures by the Twisting Method

I. S. Tomashevskaya

On the Equation of Motion of Pendulum Seismographs

P. I. Khristichenko

Bulletin (*Izvestiya*) March, 1961, Academy of Sciences, USSR, Geophysics Series.

Elastic Waves with Generalized Velocity in Two-Dimensional Bimorphic Models

Yu. V. Riznichenko, O. G. Shamina, R. V. Khanutina

In this paper formulas are derived for the propagation velocities of long longitudinal and transverse waves in thin bimorphic and polymorphic plates in two-dimensional modeling of seismic waves. As a result of experiments carried out, the formation process of waves with a generalized velocity has been investigated, and the field of application of the long-wave theory has been evaluated. A bimorphic model of a gradient medium has been designed and constructed by which the amplitude characteristics of the longitudinal waves have been investigated.

Refraction and Reflection Indices for an Elastic Wave at a Layer

G. S. Pod"yapol'ski

Formulas for the numerical calculation of the refraction and reflection indices of elastic waves at a layer of constant thickness are obtained. These formulas are given, in particular, in terms of the refraction and reflection coefficients at the boundaries of the layer. These coefficients are treated as operators that transform the waveforms and their frequency patterns. Certain limiting cases are considered.

The Seismicity of Turkmeniya and Northeastern Iran in 1957–1959

N. K. Bulin, V. I. Bubnova and E. A. Pronyaeva

Experimental Verification of Optimum Conditions for Continuous Neutron Logging

Yu. P. Bulashevich and I. N. Sen'ko-Bulatnyi

Basic propositions in the theory of continuous neutron logging were experimentally verified. The experimental and theoretical data in connection with neutron logging in Mesozoic bauxite deposits were found to be in good agreement. Greater precision was achieved in the quantitative theoretical relationships. Practical recommendations for continuous neutron logging are given.

On the Equivalence of Magneto-Telluric Sounding Curves

M. V. Kolmakov and N. P. Vladimirov

The equivalence of magneto-telluric sounding curves is discussed by analyzing the equivalence equation and the curves for an electrically homogeneous half-space containing a high-resistivity layer. The results are compared with equivalence in vertical electrical sounding. The combined use of magneto-telluric sounding and vertical electrical sounding is recommended.

Of Ferruginous Quartzites to Interpret the Magnetic Anomalies of the KMA

The Oskolets sector of the KMA (Kursk Magnetic Anomaly) is used for a comparison of the results of an interpretation of a surface magnetic survey and direct measurements of magnetic susceptibility κ and remanent magnetization I_r and an attempt is made to explain the reason for the development of local minima.

The Kola Peninsula Earthquakes of 2 and 9 February 1960

G. D. Panassenko

Some Features of the Seismic Process from a Study of Earthquakes in Tadzhikistan

V. N. Gaiski

The Properties of a System with Accumulation and Transformation of Frequency in the Case of a Perfect Analyzer

YU. V. KHOMENYUK

An Interesting Property of Theoretical Magneto-Telluric Sounding Curves

M. V. KOLMAKOV

1. The symmetry of MTS curves has been proved for specified relations between the parameters of geologic sections. 2. The symmetry characterizes $|\rho_2.\rho_1|$ and ϕ curves. 3. Symmetry reduces the work of calculation and the number of curves to one-half. 4. The identical shapes of symmetric curves provide a graphic means of comparing MTS resolving power for different types of sections.

A Method of Studying the Electrical Properties of Fossil Coals

S. A. TOPORETS

Bulletin (*Izvestiya*) May, 1961, Academy of Sciences, USSR, Geophysics Series.

Some Results of a Detailed Study of the Seismicity of the South Kuril Islands

S. A. FEDOTOV, V. N. AVER'YANOVA, A. M. BAGDASAROVA, I. P. KUZIN AND R. Z. TARAKANOV

Low-Frequency Seismometer Arrays

L. P. VINNIK

The seismometer-array method can be used for a wide range of problems which have to be solved by seismology. A formula is deduced for magnification and frequency characteristic of a seismometer in an array with direct galvanometric registration. A method of computing arrays for certain areas is given.

Reflection and Refraction of Plane Elastic Waves at the Boundary of Two Anisotropic Media

I. O. OSSIPOV

The problem of the reflection and refraction of plane elastic waves at the interface of two anisotropic media with three elastic constants is examined in the present paper. This problem is solved by the known method of V. I. Smirnov and S. L. Sobolev, which was subsequently used by V. A. Sveklo to solve dynamic problems of elasticity for the case of anisotropic media.

Special Features of the Stressed State in Foci of Earthquakes in the Baikal Region

A. V. VVEDENSKAYA

Observations of Long-Period Seismic Waves at the Simferopol Station

V. T. ARKHANGEL'SKY, D. P. KIRNOS, I. I. POPOV AND V. N. SOLOV'EV

A brief description is given of a model of a vertical seismograph for recording seismic waves with periods of 20–300 sec. Results of tests made of this instrument are cited and some results of observations made with it at the Simferopol seismic station reported. During the Chilean earthquake of May 22, 1960 the instrument recorded waves with periods up to 480 seconds.

On the Determination of Parameters of Layers of Intermediate Thickness from the Spectra of Reflected Waves

L. L. KHUDZINSKI

The paper suggests a method for the determination of a layer thickness (with the wave velocity in the layer being known) or of the propagation velocity of waves within it (with the thickness known) from the spectra of the waves reflected from the layer. Areas of application of the method are discussed. An evaluation is submitted of errors caused by the effect of the spectra of the shot and of the absorption and frequency characteristics of the recording channel, and by the presence of the interference background.

The Resolving Power of Methods of Gravitational-Field Separation

K. V. GLADKII

The representation of anomalies and errors of observation as random functions is used to study the resolving power of methods of decomposition of two-dimensional gravitational fields. Methods of calculating resolving power are considered, and the choice of optimum parameters of operation for the calculation of higher derivatives is investigated.

Structure of the Earth's Crust in Eurasia from the Dispersion of Surface Waves

B. N. SHECHKOV

The two-layered structure of the earth's crust in Eurasia is analyzed from surface wave dispersion for the following trajectories: Central Asia—Kuril Islands; European part of the USSR—East China Sea—Japanese Islands. The thickness of the crust is deduced simultaneously from Love and Rayleigh waves. The data obtained are compared with each other.

The Structure of the Earth's Crust in Siberia and in

the Far East from Love and Rayleigh Wave Dispersion Data

E. F. Savarensky and B. N. Shechkov

The Influence of the Folded Basement upon the Thermal Character of the Meso-Cenozoic Strata in the West Siberian Plain

G. A. Cheremenski

1. The location of the isothermal surfaces above the basement of the Plain depends mostly on the ratio of the heat conductivity of the basement rocks to that of the overlying stratum. This dependence may be obscured by hydrogeological, tectonic, and other factors.

2. The value of the average geothermal gradient of the meso-cenozoic layer increases in the near-boundary regions of the West Siberian Plain and in areas where the basement rises. Such an increase of the geothermal gradient is generally produced by the thermal anisotropy of the meso-cenozoic strata.

Microseisms on the Bed of the Black Sea

F. I. Monakhov

A Study of the Volumetric Compressibility of Marble at High Pressures

G. A. Adadurov, D. B. Balashov and A. N. Dremin

The Solution of a Boundary Value Problem for a Hyperboloid of Revolution in Electric Surveying

A. M. Gluzmann

In the present article, we obtain the potential distribution generated by a point current source at the boundary of a half-space, in the presence of a dividing surface in the form of a hyperboloid. This distribution is obtained by solving the Laplace equation in a system of degenerate ellipsoidal coordinates. For deriving certain coefficients, we use an integral theorem connected with the Mehler-Fock expansion. The expressions for the potential functions are given in the form of real integrals.

Capacitance Detectors for Ultrasonic Pulses

B. N. Ivakin and Yu. F. Vassil'ev

A Pulse Generator for Exciting Piezoelectric Emitters

L. N. Rykunov and S. D. Selyuminov

The Propagation of Ultrasonic Waves in Frozen Sandy-Clayey Rocks

A. D. Frolov

On the Magnetic Powder Method of Studying Pyrrhotite Ores

M. A. Grabovsky, O. N. Zherdenko and Yu. P. Skovorodkin

Auxiliary Apparatus of the Seismic Stations of Northern Tien-Shan

V. M. Fremd

Conference on Deep Seismic Sounding

PERSONAL ITEMS

T. W. SPENCER has been promoted to Senior Research Physicist, Theoretical Seismology in the Geophysics Research Section, La Habra Laboratory.

ROY O. SMITH, formerly manager of States Exploration Co.'s Gulf Coast area, has opened geophysical consulting offices in Houston. Smith was with Robert H. Ray Co. and Southern Geophysical Co. before joining States Exploration.

FRANS H. HAMMONS, staff geophysicist with Pan American Petroleum Corp., has been transferred to New Orleans, from Lafayette, La.

HUBERT B. HUNT, geologist for Atlantic Refining Co. in Houston, has joined Sinclair Oil & Gas Co. as geophysicist in Oklahoma City.

J. R. JACKSON, California area geologist, Humble Oil & Refining Co., has been named exploration Mgr. for the Los Angeles area.

KENNETH E. MYRON, New York staff geologist, Texaco, Inc., has been transferred to Los Angeles as assistant to the division Manager.

R. JODRY, research geologist with Sun Oil Co., has been transferred to Richardson, Texas, from Billings, Montana.

H. J. MCGREW, geophysicist with British American Oil Co. in Calgary, has been named geophysicist for Gulf Research & Development Co. in Harmarville, Pa.

M. DEAN KLEINKOPF, lead geophysicist for California Oil Co. in Salt Lake City, has been promoted to lead geophysicist in Denver. He will be in charge of gravity and magnetic interpretation and operations in the Rocky Mountain area.

FLOYD L. CASH, Arlington State College, Arlington, Texas, has been elected Editor of the Society of Professional Well Log Analysts.

H. GUYOD, Consultant, has been elected Member-at-Large of the Society of Professional Well Log Analysts.

MARTIN C. KELSEY, JR., formerly with the research and development department of The Atlantic Refining Co., is now Vice-President of Palmer Johnson Boats, Inc., in Sturgeon Bay, Wisconsin.

HUGH MCCLAIN, JR., formerly with the Atlantic Refining Co., is now part owner, Vice-President, and General Manager of Smith Rubber Craft, Inc., of Hattiesburg, Mississippi.

T. C. RICHARDS, formerly with Triad Oil Co., Ltd., is now a geophysical consultant. His new address is Burgage Cottage, Westerham, Kent, England.

J. R. HEGGBLOM, formerly Exploration Coordinator, Bolivian Gulf Oil Co., is now General Manager of the Caribbean Gulf Oil Co. He is located in San Jose, Costa Rica.

DAVID W. STRANGWAY has been appointed Asst. Professor in the Geology Department of the University of Colorado, Boulder Colorado. His duties will include teaching and research in the field of geophysics. He was previously employed as a research geophysicist for the Bear Creek Mining Co., Denver, Colorado.

ROGER PEMBERTON will head the new Exploration Division of Aero Service Corporation, Philadelphia. Before moving to Philadelphia in his new post, Pemberton was president of the Canadian Exploration Geophysical Society. He is also a member of the AIME, Canadian Institute of Mining & Metallurgy, SEG, and the American Society of Photogrammetry.

CHALMER J. ROY, professor and head of geology at Iowa State University, will spend six months in India starting September 1, 1961 under the auspices of the Department of State. He will conduct seminars and serve as consultant on educational problems in the geological sciences at leading Indian Universities.

GSI's Gulf Coast and Southeastern operations have been combined into Eastern Operations. The new section will be headed by T. P. ELLSWORTH, formerly manager of operations on the Gulf Coast with G. A. (JIM) HOWARD as manager.

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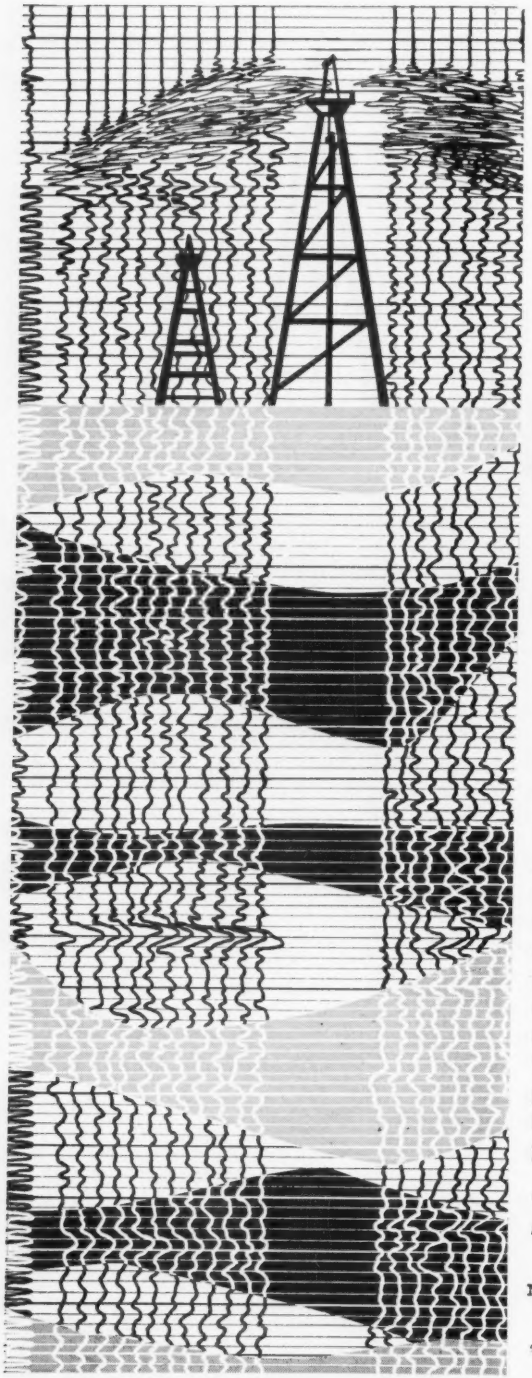

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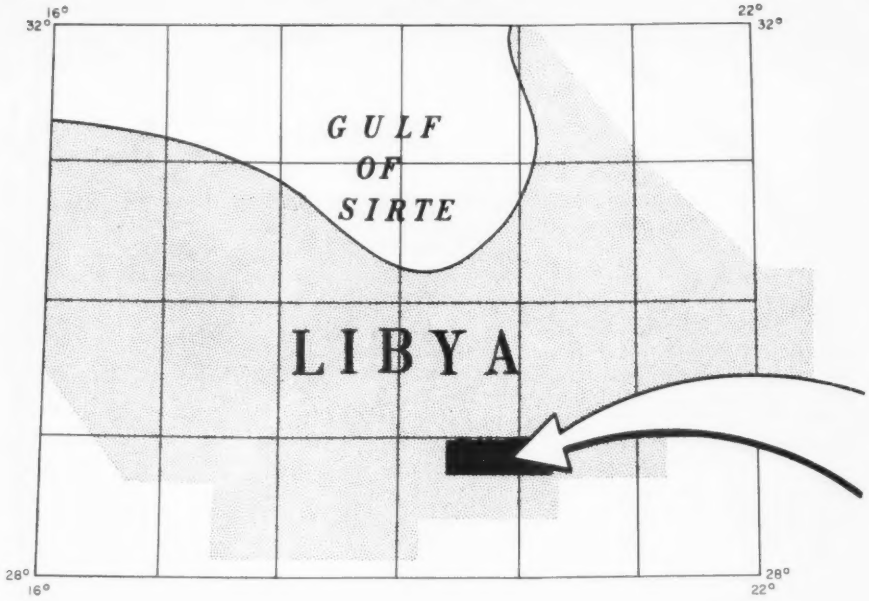

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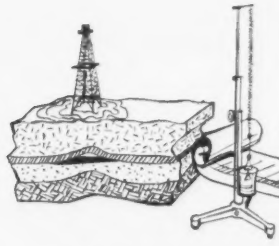

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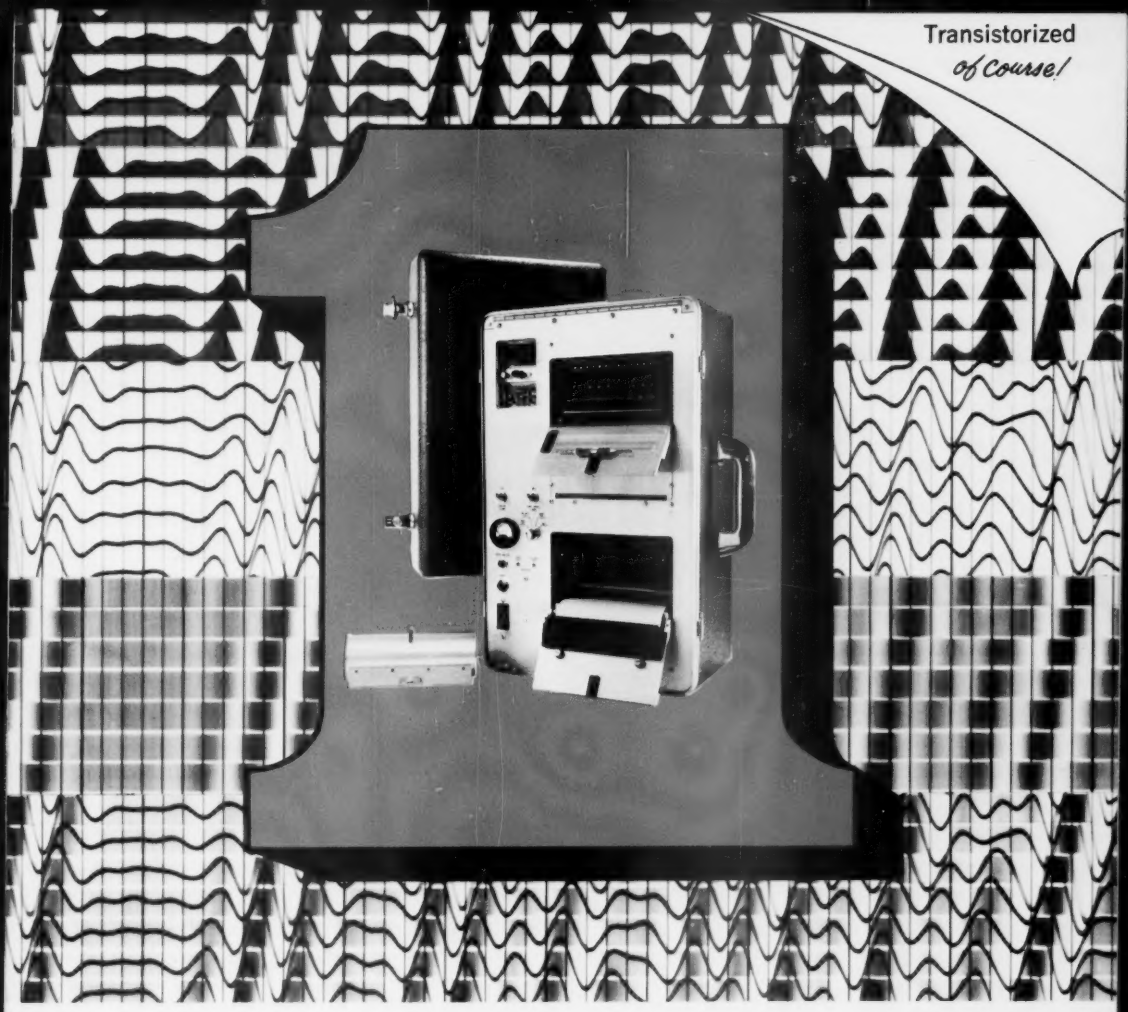

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CONDENSED SPECIFICATIONS

Channels: 24 geophysical
4 auxiliary (Time break, up-hole, 100 cps and noise cancelling)

Frequency response: 1 cps to 300 cps within 1 db; 3 db down at 500 cps

Signal-to-noise ratio: 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

Harmonic distortion: Less than 1%

Crossfeed: Below noise level of recording system

Relative timing accuracy: ± 0.25ms

Power requirement:

	Standby	Operating
Record	2 amp.	7 amp.
Playback	1.5 amp.	6.5 amp.

12 volts D.C.

Dimensions: MR-20 Recorder—8¼"W x 24½"H x 15"D
MU-20 Master Unit—8¼"W x 24½"H x 10½"D

Weight: MR-20 Recorder—60 lbs.
MU-20 Master Unit—45 lbs.

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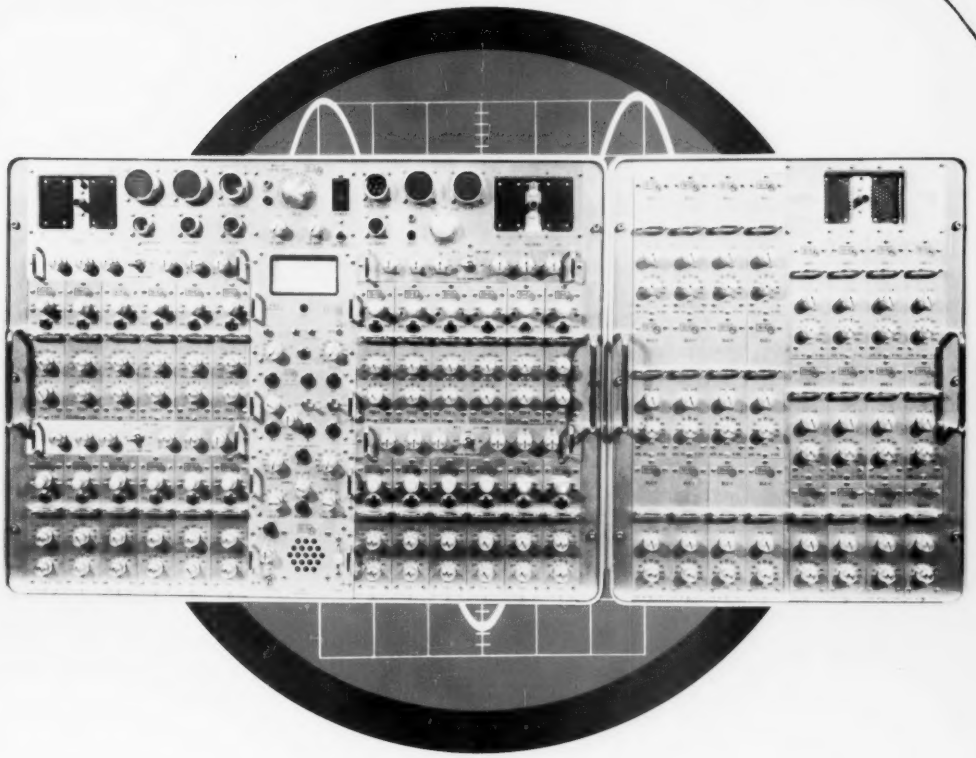
PT-100 Transistorized Seismic Amplifier



SIGNAL CONTROL

With unique light-sensitive photocells as losser elements, the PT-100 eliminates the usual amplifier AGC problems. The critical "diode-balancing" common to other types of AGC circuits is never required. There is no direct electrical coupling between AGC and signal paths to cause distortion and oscillation. Signal voltages do not cause distortion when applied across losser elements as with diode bridge circuits. Drift and temperature instabilities are eliminated. There is a useful operating range of from one microvolt to one volt input — 1,000,000 to 1! Total harmonic distortion under all normal field operating conditions does not exceed 0.5% including heavy reflection standout. External 4 kc signals may be used for programmed-gain operation during amplitude studies. AGC performance down to 5 cps allows use of the PT-100 in refraction work **with AGC control.**

FREQUENCY RESPONSE

The broad band response extends from 3 to 500 cps. Ten logarithmically-spaced cut-off frequencies are provided — from 16 to 135 cps for the low-cut and 23 to 235 cps for the high-cut filter positions. One or two sections (18 or 36 db/octave) may be used.

NOISE

Noise is less than 0.3 microvolt for "filter-out" bandpass and drops to 0.1 microvolt for normal filter settings — as good or better than most vacuum tube amplifiers.

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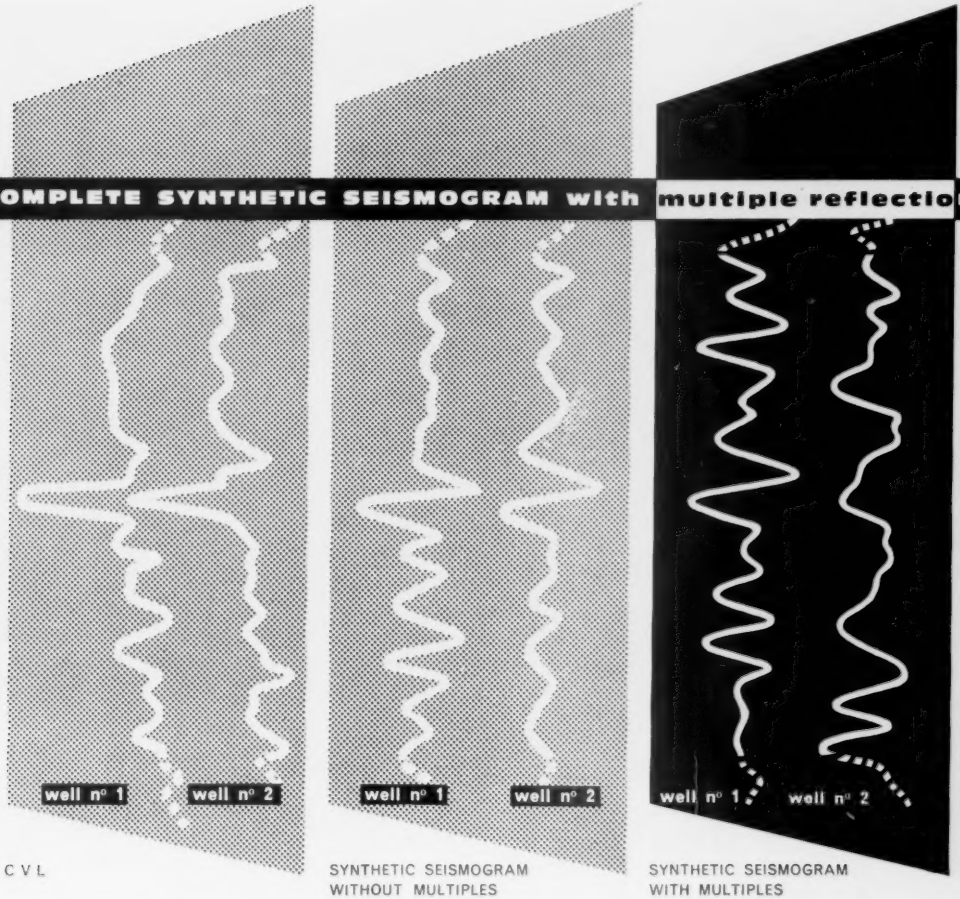

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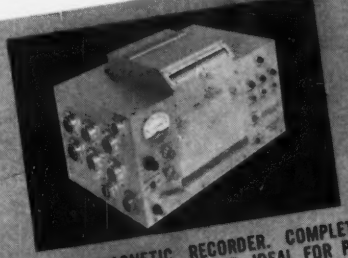

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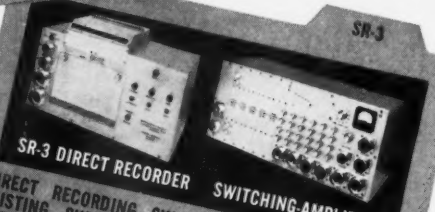

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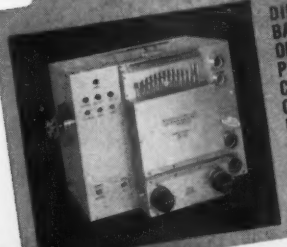

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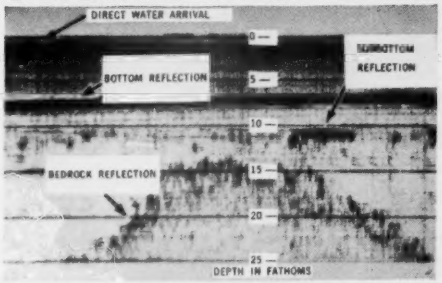

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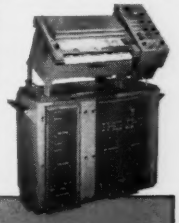

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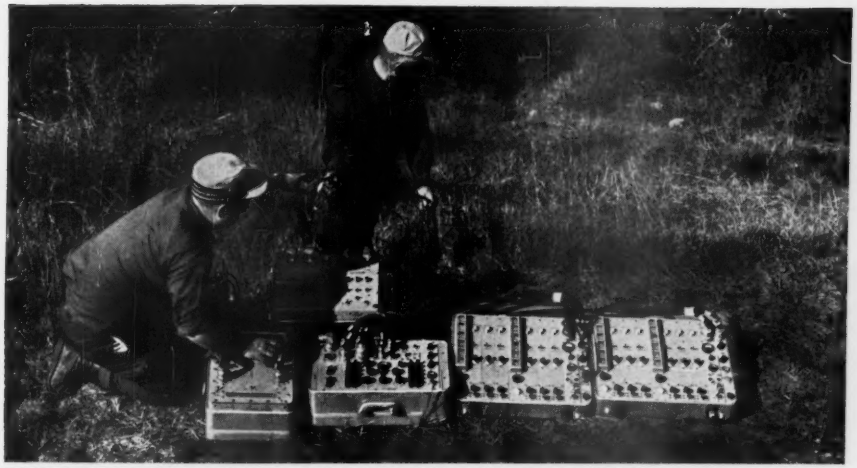

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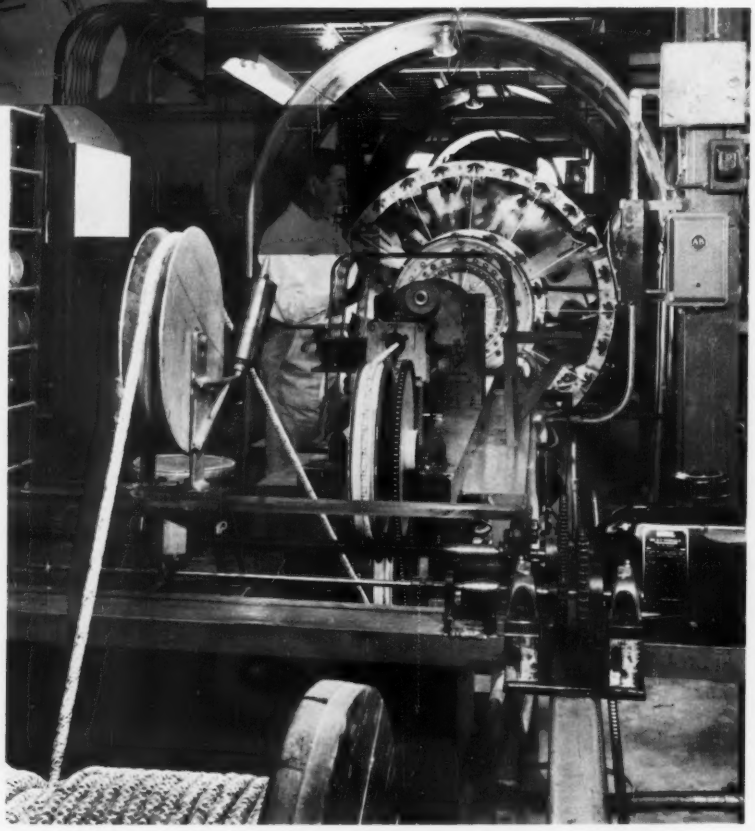

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III. The outside cable sheath is permanently interlocked with Polymer to the conductors themselves for rugged, long-lasting cable that's tops for land or water use. Write or call for literature, details and prices today!

* **POLYMER FILLED**
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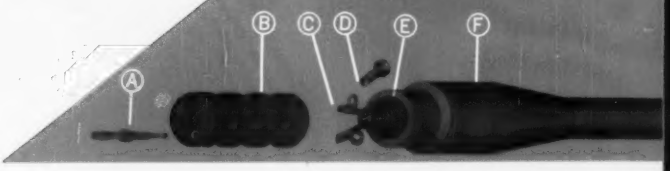
MODEL RVMP-18

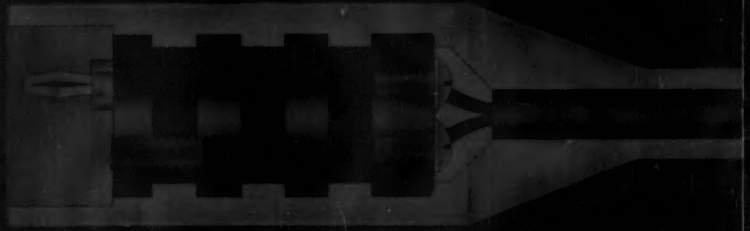
THE WATER PROOF "JR." FIELD REPAIRABLE PLUG

1 *take apart*



Ⓐ Famous Vector Replaceable Banana Pin
Ⓑ Contact Block (fits inside Nipple)
Ⓒ Crimp Lug
Ⓓ Screws. (Only two to attach Lugs to Contact Block)
Ⓔ Cable Jacket
Ⓕ Rubber Nipple

2 *re-assemble*



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This is the C-850 in Pan American's Houston office.

Pan American Uses EIC's C-850 to Handle Its Data Analysis Problems

Pan American Petroleum Corporation owns several C-850 central office seismic data reduction systems, purchased to provide the flexibility needed to meet the firm's broad data-handling needs.

You too can simplify your toughest data analysis problems with this versatile playback system. Any data-handling technique you may need can be applied with the C-850, the most flexible single-system available for sequential playback of magnetic tapes.

The C-850 lets you make maximum static corrections of ±100 ms and dynamic corrections up to 400 ms (at a maximum rate of 500 ms per sec). Timing accuracy is ±1 ms. Any geophone spread length or arrangement can be handled.

During playback, time-corrected seismic data are plotted simultaneously to photographic cross sections. You can choose conventional-trace, variable-area, or variable-density cross sections, or any two of these three. Seismic data can be referenced to any desired datum plane on the cross-section plots. As many as 864 traces can be recorded on a single cross section as large as 72 x 72 in.

Corrected data are re-recorded during playback for future evaluation. As many as 12 channels of re-recorded tape can be played back for mixing, compositing, or stacking to cross-section plots.

Call or wire EIC for detailed specifications on the C-850.

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Normal moveout corrections up to 400 ms are available at a maximum rate of 500 ms per sec. Maximum weathering and elevation corrections of ± 100 ms can be applied. Corrections are inserted easily and rapidly by a keyboard input unit.

Timing lines on cross-sections can be recorded directly from field timing signals, giving you accurate trace plots that are in true relation to each other and to record time. A 100 cps tone (supplied by the playback system) may also be used to indicate time on the sections. Seismic information can be accurately referenced to any desired datum plane. Either conventional-trace or variable-density cross-sections (or both) are plotted photographically on 24 x 72-in. paper or film. This system can be supplied with any standard-size tape transport.

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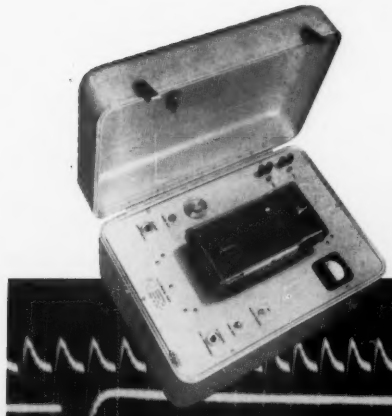
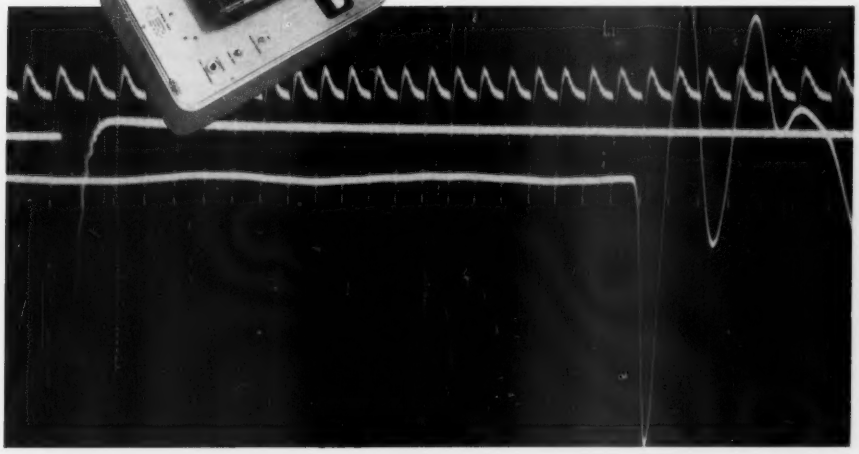


EIC

This is a typical timing record produced by the GT-2.



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EIC's new Model GT-2 recording interval timer combines in a single rugged package both a 90-volt blaster and a highly accurate timer for recording uphole time. This completely transistorized instrument gives you accuracy of ±0.5 millisecond. It weighs only 29 pounds.

The GT-2 produces a permanent record on Polaroid film. Developing time for the record is only 10 seconds.

Data are presented in conventional seismogram form, with timing, time-break, and first-break traces. Time interval is measured from the time break to the geophone first break. Timing marks are accurately recorded at 1/100-second intervals.

Three speeds are available, 0.2, 0.3, or 0.4 second. Equivalent paper speeds are approximately 17, 13.5, or 10 inches per second.

For an engineering data sheet on the GT-2, just send us your name and address. If you wish, we will arrange a demonstration for you soon.

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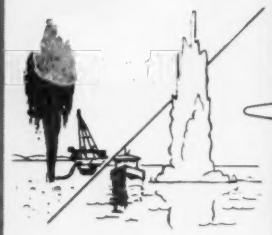

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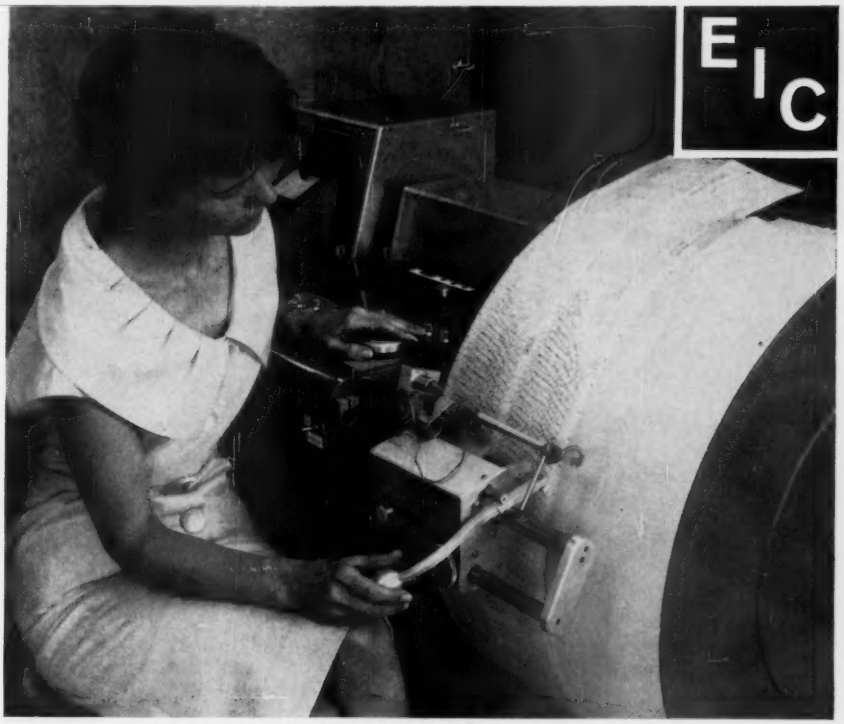

Transcorder in operation at Canadian Magnetic Reduction, Calgary.

TRANSCORDER BUILDS NEW CANADIAN DATA-TRANSCRIBING SERVICE

Canadian Magnetic Reduction (Alberta) Limited, Calgary, has used EIC's Transcorder to offer its clients a new service based on transcribing seismic data from paper records onto magnetic tape. Since the Calgary firm installed its Transcorder early in 1961, customer demand has kept it busy constantly.

"Our clients have been pleased with the fidelity and usefulness of tape-recorded data transcribed from their paper records by our Transcorder," said Mr. Peter J. Savage, general manager of Canadian Magnetic Reduction.

"The need for this new instrument and the quality of the work it produces are shown by the fact that we have kept our Transcorder working two shifts daily for months."

The Transcorder transcribes seismic data onto any standard geophysical tape from paper records or from other AM tapes in common use.

Magnetic tapes produced by the Transcorder can be processed by playback systems that permit mixing, selective filtering, correcting for moveout, weathering, and elevation, and presentation in cross-section form with any type of display selected by the interpreter.

Call or wire EIC for detailed specifications on the Transcorder.

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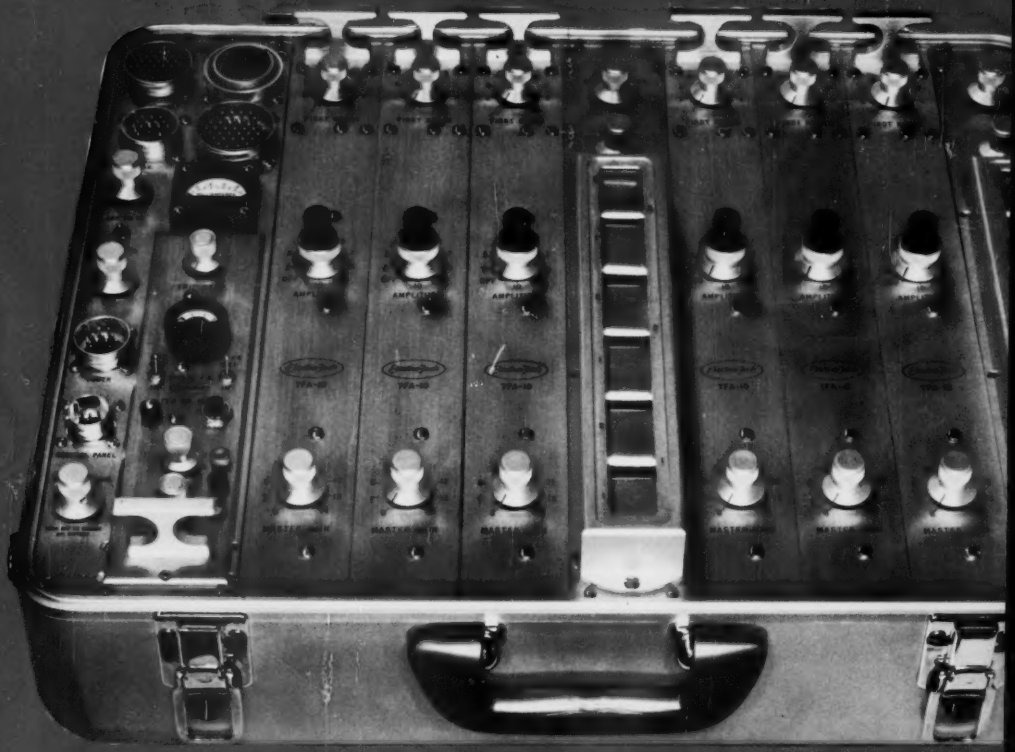

The best all around transistorized reflection amplifier available in the industry, ETL's TFA-10 combines the best features of conventional vacuum tube models with the compactness and power efficiency made possible by transistor circuits.

EASY MAINTENANCE! The TFA-10 was field tested under the most rugged terrain and climatic conditions for ONE YEAR before being introduced on the market. Each channel employs only a small number of ONE TYPE of transistor throughout its entire circuit (other systems require many transistors of varying types) and all transistors have plug-in sockets for further quick and easy maintenance.

COMPACT SIZE! The TFA-10 requires FAR LESS TOTAL POWER to operate than comparable vacuum tube amplifiers need just to heat the filaments. It operates completely under its own power with SELF-CONTAINED RECHARGEABLE BATTERIES, thus giving additional

PLUG-IN FILTERS! Compe ferent band pass filters are pac container. A front panel switch or by plugging in different cont of filter combinations are availa

CONDENSED SPECIFICATIONS:

GAIN: 114 DBV
AGC DYNAMIC RANGE: 120 DBV
OUTPUT: Tape 540 mv—120 ohms impec
Galvo 34 mv— 70 ohms impec
DISTORTION: Less Than 1% with AGC
NOISE: 0.2 microvolts
TEMPERATURE RANGE: —40°F. to plus
WEIGHT: 45 pounds with case
(12 channels with self-contain
DIMENSIONS: 21" long x 17" wide x 7½"
(in case)

*Manufactured under license from Weste

vings in weight.
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ged in a plug-in
ects either filter,
ers, any number
e.

ce
ce
5 cps.

0°F.

batteries)
eep

Geophysical Company

Although a relatively recent development, the SA100-1 has gained a world-wide reputation as one of the finest, high fidelity seismic amplifiers on the market. It exhibits extremely low AGC distortion, ranging from less than 1% up to 100 mv input, to less than 2% up to 0.5 V input. The AGC range is ½ microvolt to 1 volt input with three time constants selectable from the front panel. Ten low pass and ten high pass filters are provided, each with two different attenuation rates available. The SA100-1 weighs approximately 300 pounds and must be truck mounted. Send for complete specifications on this superior instrument.

SEISMIC AMPLIFIER

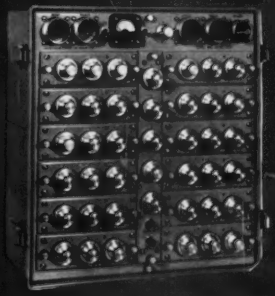
SA100-1

Manufactured under license from Seismic Explorations, Inc.

M4E-12

REFRACTION-REFLECTION SEISMIC AMPLIFIER

A lightweight, vacuum tube amplifier unsurpassed in versatility



One of ETL's most versatile units, the M4E-12 is unmatched by any other amplifier in its overall trouble-free performance.

The M4E-12 is highly sensitive and has three separate outputs: for driving direct magnetic recording heads, FM modulators and galvanometers. The first provides sufficient power to drive normal types of recording heads, eliminating the need for booster amplifiers.

Automatic filter switching, providing different filters before and after first breaks, is ideal for conducting near surface refraction and/or reflection surveys.

The M4E will handle up to 100 millivolts input signal with negligible distortion in any of three AGC speed conditions. The AGC threshold is 0.5 microvolts.

SPECIFICATIONS:

Power Requirements:
One Channel
"A"— 12 volt at 0.75 amp
"B"—180 volt at 3.0 ma
Rack with 12 Channels and Control Unit
12 volt at 10 amp
180 volt at 42 ma
Dimensions: 15" long x 14" wide x 6" deep
Weight: 43 pounds COMPLETE

INPUT UNIT
14" long x 8" wide x 4½" deep (in aluminum case)
Weight: 8 pounds COMPLETE

This easy to maintain, simple to operate unit is designed for long, economical service in conducting short or long range seismic refraction surveys. All components are easily accessible and the PRA2 channels can be substituted for M4E channels in the M4E rack, making both units highly flexible in their use.

Besides GAIN and OUTPUT LEVEL controls, each channel is provided with a low pass filter with several cut-off frequency selections. The unit is packaged in a rust-proof reinforced aluminum case with baked enamel finish.

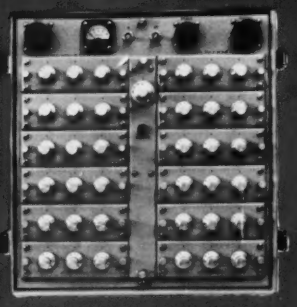
SPECIFICATIONS

GAIN 120 DB (five equal steps of fixed gain)
Input Impedance: 150 ohms
Output Impedance: 50 ohms
Over-all Frequency Response: 3 to 190 cps with filters out.
Power Requirements (12 channels):
12 volts dc at 3.6 amp
180 volts dc at 30 ma
Dimensions:
15" long x 14" wide x 8" deep (with cover)
Weight: 35 pounds COMPLETE

PRA2-12

REFRACTION SEISMIC AMPLIFIER

A flexible system that is economical and portable.



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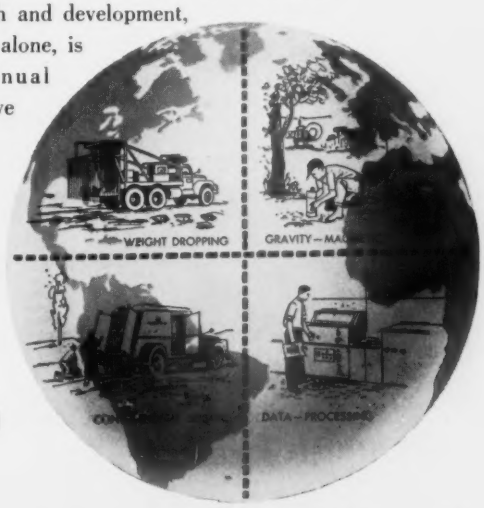

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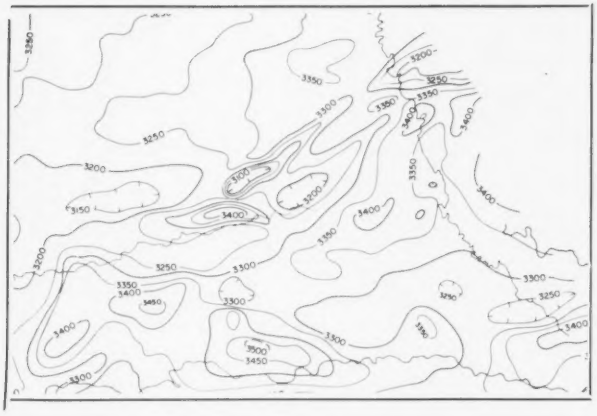

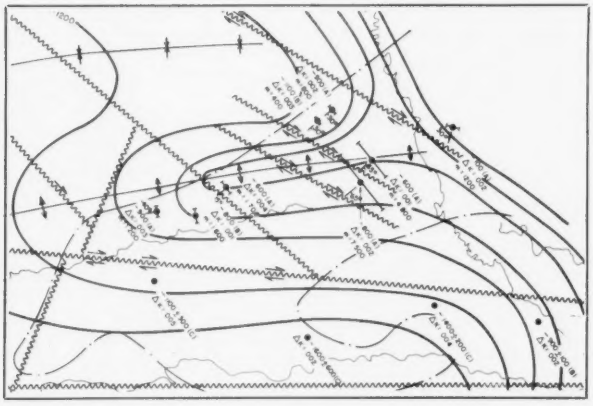

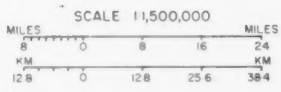

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GEOMETRY
of Sandstone Bodies

To the ancient Greeks, a geometric figure was a thing of beauty. To a petroleum geologist, a sandstone body in which oil and gas have accumulated is a thing of beauty also—especially if he finds it. Our latest AAPG special publication should help in doing just that. Here are some definitions of interest:

(1) *geologist* (n.) One versed in geology; a geological student or investigator.—*Webster's Dictionary*, 2nd Edition.

(2) *geologist* (n.) A man capable of seizing a few ill-related observations and conceiving in three or four dimensions a structure of great utility and beauty.—*T. A. Baldwin*, 1960 meeting of the AAPG-Pacific Section.

(3) *geometry* (n.) The science that treats of the properties and relations of spatial magnitudes.—*Webster's Dictionary*, 2nd Edition.

(4) *geometry* (n.) Spatial relationships of sandstone deposits within the sedimentary framework.—*The Editors.*

Working under definitions (2) and (4), the editors have put together a symposium of thirteen papers, which consider most types of sandstone bodies and their genesis—modern, ancient, and experimental. Nine were presented at the Atlantic City meeting, April 1960, three were prepared for this volume, and one is reprinted from the *Bulletin*. Criteria stressed in all these papers were: timeliness, conciseness, and usability. After reading them you will see, we believe, that the authors have achieved an overall structure of "utility and beauty."

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Among the authors are four oil company geologists, four university professors, and three federal or state survey geologists. Additional participants include the 21 men making up the AAPG Sandstone Reservoir Committee, and the many others who worked with them to provide the information and opinions found in the paper "Characteristics of Sandstone Reservoirs in the United States," which assembles data from 7,241 sandstone oil and gas reservoirs.

One, "Prospecting for Stratigraphic Traps," by Daniel A. Busch, received the George C. Matson award for the best paper presented at the 1959 annual convention. Since its appearance in the Dec. 1959 *Bulletin*, it has become one of the most widely quoted papers of its kind.

Geometry of Sandstone Bodies deals both with the primary sedimentary unit, such as a single bed, and the composite unit generally referred to as a formation or larger stratigraphic unit. Its range of coverage includes geological and geographic distribution, sandstone types, and methods of study.

The only rewards received by the authors and editors are seeing their work in print, and the knowledge that they are contributing to objects of the Association—"advancing the science of geology" and "the dissemination of facts relating to the geology and technology of petroleum and natural gas."

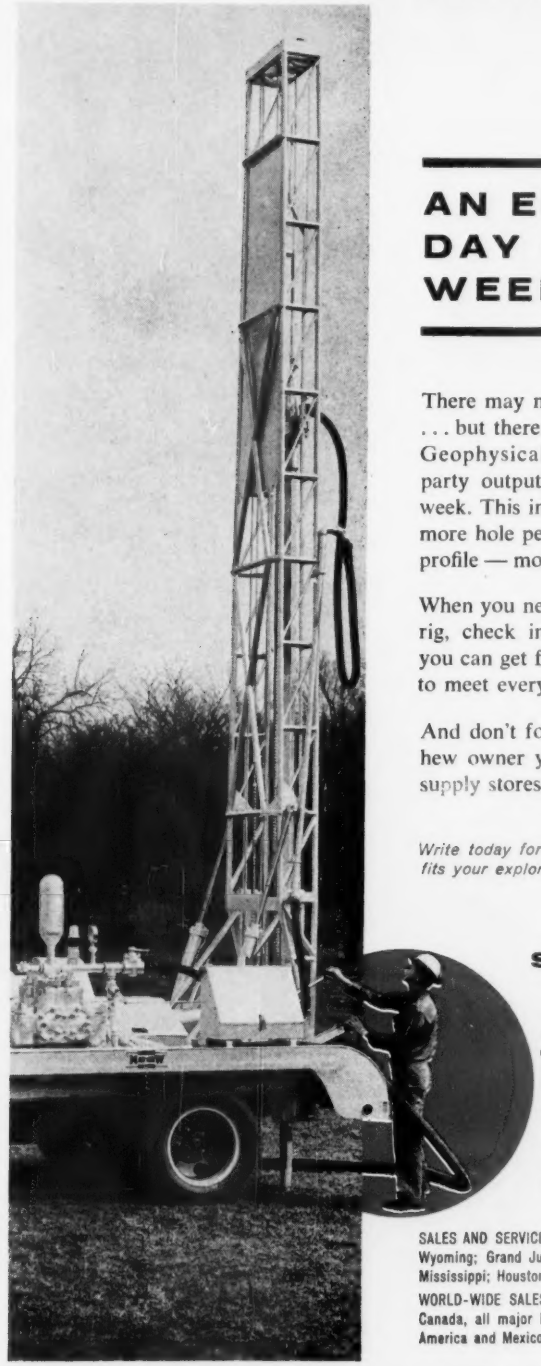
We wish to take this means to congratulate all those concerned with the publication of *Geometry of Sandstone Bodies*, and, at the same time, to call this special volume to your attention.

AAPG Executive Committee

Mason L. Hill

Mason L. Hill, President

Geometry of Sandstone Bodies (1961). 13 papers, 240 p., 177 figs., 2 pls. Index. Cloth. Members—$4.50; Non-Members—$5.50; postpaid. Send remittances to: AAPG, Box 979, Tulsa 1, Oklahoma.



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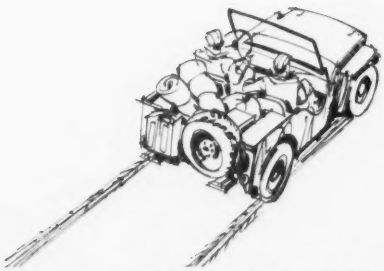

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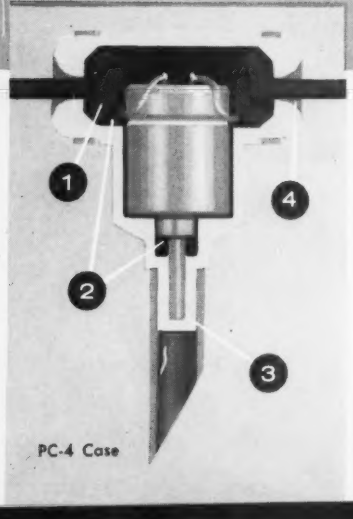

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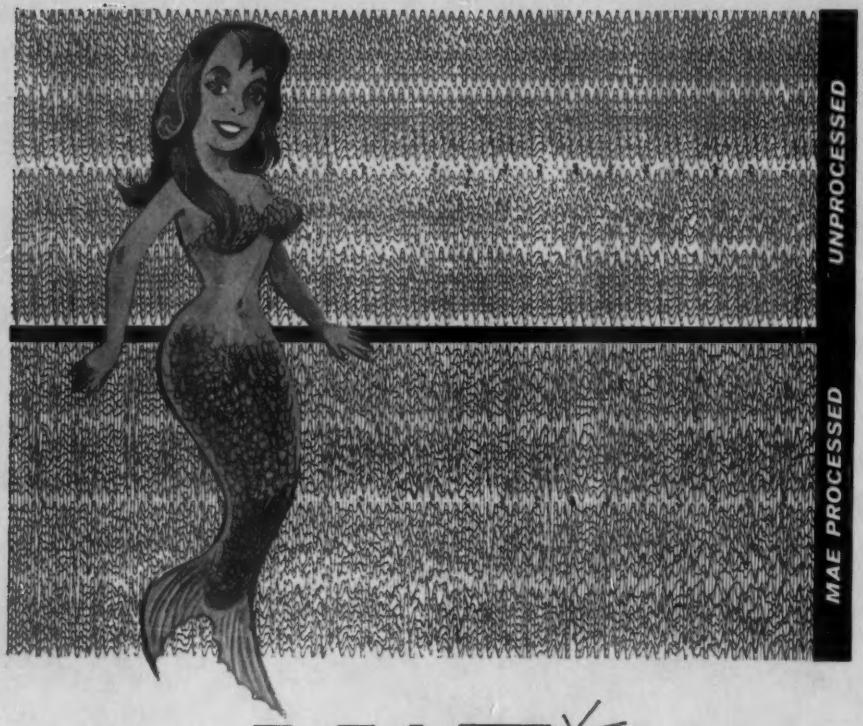

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